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OPTICAL METHOD FOR DETERMINING CARRIER LIFETIMES IN SEMICONDUCTORS

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The mean lifetime of free carriers in a semiconductor is identical with the decay time of the photoelectric effect. The rise or the decay of the excess carrier density Δn, caused by illumination, is governed by the equation

$$\partial \Delta n/\partial t = Q - \Delta n/\tau. \quad (1)$$

Q is the number of photons absorbed per unit volume and time, each photon giving rise to a hole-electron pair, t is the time, and τ is the mean life of the carriers – electrons or holes. For the steady state, we obtain

$$\Delta n_S = Q_S \tau. \quad (2)$$

Besides increasing the electrical conductivity, the photoelectrically liberated carriers cause an increase in the infrared absorption of the semiconductor. This effect has been observed for germanium[1,2] and quite recently for silicon.[3] The transmittance due to the photogenerated free carriers is

$$T = \exp(-\Delta n \sigma l), \quad (3)$$

where σ is the absorption cross section (which is a function of the wavelength of the transmitted light) and l the length of the absorption path. The background transmittance is constant and may therefore be disregarded. Moreover, multiple reflections are ignored.

Suppose now that a constant illumination, leading to an excess carrier concentration $\Delta n_S = Q_S \tau$, is interrupted periodically. The relationship between the intensity of exciting illumination and time is thus represented by the curve I in Fig. 1. If there were no relaxation, this curve would also represent Δn as a function of time (with appropriate adjustment of the ordinate scale). If the mean life, τ, of the liberated carriers is short or if the frequency of interruption, f, is low, then the real curve obtained from the solution of Eq. (1) with $Q = 0$ and $Q = Q_S$, respectively, will deviate slightly from the rectangular shaped curve I. If on the contrary, the mean life is long or the frequency high, then the modulation of the illumination will cause a small ripple of the carrier density about the mean value $\Delta n_S/2$ (curve III in Fig. 1). In each case, the mean value of Δn is $\Delta n_S/2$.

In the infrared wavelength region studied here, only thermal or pneumatic detectors are applicable for the measurement of the transmitted radiation. These have time constants of several hundredths of a second, whereas the mean lifetimes for the elementary semiconductors, germanium and silicon, amount at most to some milliseconds. For the high frequencies which are necessary for determining the lifetime in

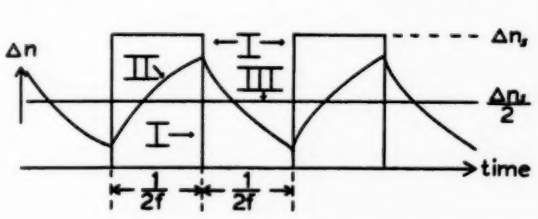

FIG. 1. Density of photoliberated carriers, Δn, as a function of time for periodically interrupted illumination. Curve I: $f\tau \to 0$; Curve II: intermediate $f\tau$; Curve III: $f\tau \to \infty$.

this case, the radiation detector will therefore measure a mean value $\overline{T}$ over several periods rather than the instantaneous transmittance. This mean value will however, because of the nonlinear relationship between T and Δn, depend on the modulation frequency f. In one of the two extreme cases, when $f\tau \to 0$, where curve I in Fig. 1 can be applied, we obtain immediately

$$\overline{T}_0 = \tfrac{1}{2}\{1 + \exp(-\Delta n_S \sigma l)\} = \tfrac{1}{2}(1 + T_S), \qquad (4)$$

whereas for the other extreme case, $f\tau \to \infty$ (curve III):

$$\overline{T}_\infty = \exp(-\tfrac{1}{2}\Delta n_S \sigma l) = T_S^{1/2}. \qquad (5)$$

For an intermediate value of $f\tau$, the solution of Eq. (1) with appropriate boundary conditions for each half period results in a curve like II of Fig. 1.

Obviously $\overline{T}_0 > \overline{T}_\infty$. The change in $\overline{T}$ for continuously increasing f is shown in Fig. 2. Here $\overline{T}$ on a linear scale is plotted against $f\tau$ on a logarithmic scale.[4] The curve is computed for $T_S = 0.64$. The shape of the curve appears to be only slightly sensitive to an alteration in T_S.

Measurements according to the method outlined above were made on a sample of near-intrinsic germanium ($\rho = 50$ ohm cm at room temperature) at the wave number 900 cm^{-1} using illumination from a tungsten strip lamp. The light from the lamp was chopped by a mechanical interrupter which could produce interruption frequencies up to about 5000 cps. The lower limit for f was set by the beam chopper frequency 13 cps of the spectrophotometer used. In practice, measurements were possible for $f > 40$ cps. The frequency was measured using an electromagnetic vibration indicator connected to an oscilloscope together with a calibrated audiofrequency generator.

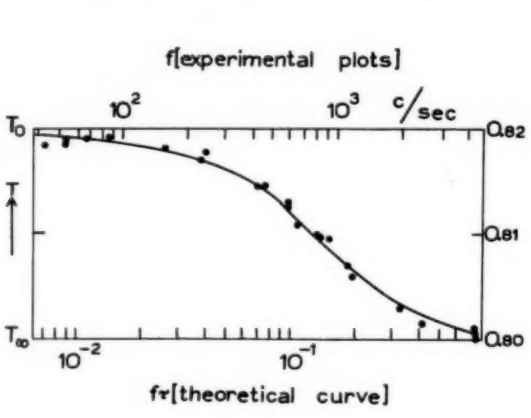

FIG. 2. Mean value of transmittance T, as a function of $f\tau$ (calculated) and of f (measured for sample of intrinsic germanium). $T_S = 0.64$ in both cases.

For the determination of the mean life τ, the experimentally obtained transmittances $\overline{T}$ are plotted against the frequency f (on a logarithmic scale). The curve is then shifted horizontally until it fits the theoretical curve $\overline{T}$ versus $f\tau$. A comparison between the two abscissa scales then immediately gives τ. From Fig. 2, we see that within the limits of error, the experimental plots do actually fit the theoretical curve, i.e., there is actually a constant mean life, which cannot be a priori postulated. The mean life obtained is $\tau = 165$ μsec, with an estimated error of ± 20 μsec. This value was confirmed by several determinations performed with the infrared beam at different distances from the illuminated surface.

The infrared absorption of Ge at 900 cm^{-1} is due to the transition of free holes between the valence sub-bands. For the germanium sample investigated, the diffusion length for holes has previously been determined[2] from the infrared absorption and was found to be $L = 0.14$ cm. The relationship

$$L = (D\tau)^{1/2} \qquad (6)$$

then gives the diffusion constant $D = 120$ cm^2/sec. This figure is not consistent with the well-established value for holes in germanium, $D_p = 50$ cm^2/sec as obtained from mobility determinations,[5] and is only barely so with $D_n = 100$ cm^2/sec for electrons in Ge. However, diffusion and recombination mechanisms may be far more complicated than assumed for the derivation of Eq. (6), e.g., because of the occurrence of trapping. Among the possible applications of the method presented here, one should mention the possibility of determining both the lifetime and diffusion length for electrons and holes independently of each other, which may be useful for the experimental investigation of carrier properties in semiconductors.

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[1] N. J. Harrick, J. Appl. Phys. 27, 1439 (1956). F. R. Kessler, Z. Naturforsch. 13a, 295 (1958).

[2] L. Huldt and T. Staflin, Phys. Rev. Lett. 1, 236 (1958).

[3] L. Huldt and T. Staflin, Phys. Rev. Lett. 1, 313 (1958).

[4] Details of the mathematical calculations will be

published elsewhere.

[5]M. B. Prince, Phys. Rev. 92, 681 (1953).

[6]A. K. Jonscher, Proc. Phys. Soc. (London) B70, 230 (1957).

EXCHANGE SCATTERING IN SUPERCONDUCTORS

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In a recent letter,[1] Anderson and Legvold have suggested that the depression of the superconducting transition temperature of lanthanum as a function of rare earth impurity content[2] may be traced to the exchange interaction between the conduction electron spins and the f-shell spins of the rare earth ions. They postulate that the conduction electrons interact via the ionic spins to modify the effective "V" in the theory of Bardeen, Cooper, and Schrieffer. We wish to comment on this view in the light of theories by Herring and by ourselves, previously presented orally[3,4] and by now submitted for publication in detail, and in the light of the further experiments reported by Matthias, Suhl, and Corenzwit.[5]

Electron interaction via virtual states of the scatterers (in the present case the ionic spins) can occur only if these are nondegenerate in energy. In the case of gadolinium, the various spin orientations are very nearly degenerate, since its closed-shell configuration admits of very little crystal field splitting, and the effective electronic interaction is therefore likely to be very small. This point is further borne out by the experiments of Lynton, Serin, and Zucker[6] with nonmagnetic impurities, which also depress the transition temperature, yet interactions via virtual states of the scatterer are here essentially ruled out.

To summarize our own view, we begin with the magnetic impurities. We believe that the effect is indeed due to exchange scattering. However, the depression of T_c seems to us to result from the fact that the scattering lowers the energy of the normal state more than that of the superconducting state. Adopting the Bardeen-Cooper-Schrieffer view of the superconducting state, we find that those scatterings in which one or both of the initial and final momentum states are within the gap contribute more to the depression of the energy of the normal state than to the depression of the energy of the superconducting state. The result is that as the impurity concentration is increased, the free energies of normal and superconducting states become equal, while the gap remains finite. A plot of transition temperature T_c versus impurity concentration ξ will not give a straight line but rather a convex curve with $dT_c/d\xi = 0$ at $\xi = 0$ and $dT_c/d\xi = \infty$ at $T_c = 0$. The value of the exchange integral required to account for the depression of T_c to absolute zero by the observed concentration of gadolinium in lanthanum is 0.15 volt, a reasonable value. As regards the shape of the curve, all cases, the newly measured ones (reference 5) as well as the (La, Gd) case seem to tend towards vertical tangency as $T \to 0$, in accord with the above predictions and at variance with a "shifted V" theory. A possible reason why at $\xi = 0$ the tangents to the $T_c = \xi$ curves are not zero will become clear in connection with our next topic, scattering by nonmagnetic impurities. In that case, we find that the free energies of the normal and superconducting states are depressed much more nearly equally; for the same magnitude of the scattering potential, the difference is an order of magnitude less than in the exchange case. The difference then has the same form that one would have obtained, had one assumed the Bardeen-Cooper-Schrieffer expression for the free-energy difference in the impure sample, and attributed the change in this difference to a reduction in the effective interaction potential. This change is effectively a consequence of the modification of the electron wave functions by the impurities. Thus it could happen in the nonmagnetic case, that the free-energy difference goes to zero by virtue of the gap going to zero with increasing concentration. Whether this is the case, or whether the difference goes to zero before the gap does, is now a question of detailed evaluation. In the exchange case there is also such a shift in effective V, but there its effects can be important only along a short initial stretch of the T-ξ curve, where $dT/d\xi$ tends to zero, while the shift in V produces a small but finite initial slope.

To summarize: If the Bardeen, Cooper, and Schrieffer theory of superconductivity is correct in its present form, the most important cause of the depression of T_c by exchange scattering is the disparity in the free-energy depressions of the normal and superconducting states. "Shifted V" effects, whether due to changes in wave function or due to electron interactions via

virtual states (even when they can occur), are small by comparison. The exchange energy between conduction electrons and ionic spins necessary to account for the observed reductions in T_C on the basis of our viewpoint is 0.15 volt, a reasonable value.

The authors are indebted to C. Herring for frequent discussions of our work on this subject.

[1]G. S. Anderson and S. Legvold, Phys. Rev. Lett. 1, 322 (1958).
[2]Matthias, Suhl, and Corenzwit, Phys. Rev. Lett. 1, 92 (1958).
[3]C. Herring, Kamerlingh Onnes Conference, Leiden, June, 1958 (unpublished).
[4]B. T. Matthias and H. Suhl, International Conference on Electronic Properties of Metals at Low Temperatures, Geneva, New York, August, 1958 (unpublished).
[5]Matthias, Suhl, and Corenzwit, Phys. Rev. Lett. 1, 449 (1958).
[6]Lynton, Serin, and Zucker, J. Phys. Chem. Solids 3, 165 (1957).

EFFECT OF HYDROSTATIC PRESSURE ON THE ANOMALOUS HALL COEFFICIENT REVERSAL IN SINGLE CRYSTAL TELLURIUM

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Pure tellurium in the extrinsic range is a p-type semiconductor, and its Hall coefficient reverses sign in the vicinity of room temperature in the usual fashion. There is a second reversal[1] of the Hall coefficient back to p-type at approximately 230°C. This anomalous reversal has been most recently verified on crystals grown by the Bridgman method by Fukuroi et al.,[2] Bottom,[3] and Nussbaum.[4] It is further shown by Fukuroi et al. and Bottom that the upper reversal temperature is independent of sample purity for their particular samples. Explanations of this phenomenon have been advanced by Fritzsche,[5] Fukuroi et al.,[2] and Callen,[6] but exceptions have been taken to some of their arguments by Gáspár[7] and Dresselhaus.[8] An effort was made by Nussbaum[9] to gain an insight into the effect of a change in lattice size on the band structure of tellurium by measuring the shift in upper reversal temperature when hydrostatic pressure was applied. This experiment was performed on the alloy 87% Te - 13% Se, whose upper reversal temperature is 177°C. Due to apparatus limitations the results were inconclusive.

Recently, large single crystals of tellurium have been grown in this laboratory by the Czochralski method.[10] These crystals are an order of magnitude purer[11] than any previously available. Pressure apparatus with a range of 0 - 30 000 lb/in², as previously used by Long,[12] was kindly made available to us by J. Taylor, Morgan State College. Hall coefficient vs temperature was measured at atmospheric and at 30 000 lb/in² pressure on samples cut from two different crystals and oriented with the c-axis (3-fold axis) normal to the magnetic field. The results as shown in Fig. 1 indicate (1) that the upper reversal temperature is 246°C, which is about 15° higher than has been previously reported, and (2) that the effect of pressure is to raise the re-

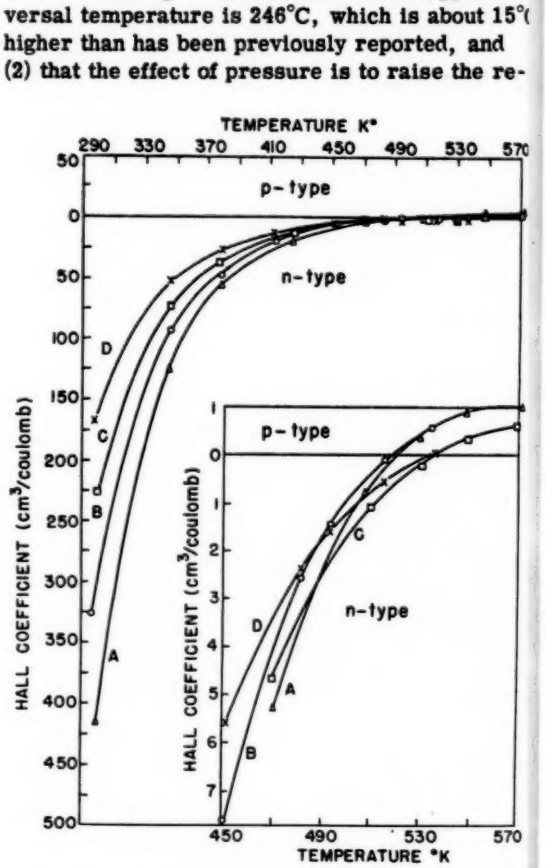

FIG. 1. Hall coefficient vs temperature for single-crystal tellurium. The inset shows the region near the anomalous reversal using an expanded scale. Curve A: Sample No. 1 at atmospheric pressure; Curve B: Sample No. 2 at atmospheric pressure; Curve C: Sample No. 1 at 2000 atmospheres pressure; Curve D: Sample No. 2 at 2000 atmospheres pressure.

versal by about 16°C, in contrast to the Te-Se alloy mentioned above, for which the reversal temperature was apparently lowered about 5°C. The impurity concentration of the two samples of Fig. 1, as determined from the Hall coefficient R at 77°K and the approximate formula $R=1/pe$ (p = carrier density, $e=1.6\times10^{-19}$ coulomb), is 7.2×10^{14} carriers/cm^3 for sample 1 and 2.2×10^{15} carriers/cm^3 for sample 2. In addition, the upper reversal temperature for a third sample with $p=7.2\times10^{16}$ was found to occur at 498°K and this demonstrates the shift of the upper reversal temperature with impurity concentration. Long[13] has computed that the hydrostatic pressure used in this experiment causes the energy gap to decrease by 0.032 ev, and this in turn is responsible both for the decrease in the lower reversal temperature which he reported and for the decrease in Hall coefficient with pressure in the region below the "crossover" point at about 217°C on both pairs of curves in the present experiment. However, the cause of the upper reversal shift still remains unknown.

[1]P. I. Wold, Phys. Rev. 7, 169 (1916).
[2]Fukuroi, Tanuma, and Tobisawa, Science Repts. Research Insts., Tôhoku Univ. A1, 373 (1949).
[3]V. E. Bottom, Science 115, 570 (1952).
[4]A. Nussbaum, Ph. D. thesis, University of Pennsylvania, 1954 (unpublished).
[5]H. Fritzsche, Science 115, 571 (1952).
[6]H. B. Callen, J. Chem. Phys. 22, 518 (1954).
[7]R. Gáspár, Acta Phys. Acad. Sci. Hung. 7, 289 and 313 (1956).
[8]G. Dresselhaus, Phys. Rev. 105, 135 (1957).
[9]A. Nussbaum, Phys. Rev. 94, 337 (1954).
[10]T. J. Davies, J. Appl. Phys. 28, 1217 (1957).
[11]H. Roth, as reported at the International Conference on Semiconductors, Rochester, August, 1958 (unpublished).
[12]D. Long, Phys. Rev. 99, 388 (1955).
[13]D. Long, Phys. Rev. 101, 1256 (1956).

NEUTRON-PROTON MASS DIFFERENCE BY DISPERSION THEORY

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An attempt to explain the neutron-proton mass difference by introducing in the divergent integrals of the second-order electromagnetic self-mass a fundamental length has been made by Feynman and Speisman.[1] They show that the proton can in fact turn out lighter than the neutron, in spite of its electrostatic energy, if the anomalous moments of the nucleons are introduced in the interaction and the integrals are cut off at sufficiently high energy. Since then it has been realized that the electromagnetic self-masses of the nucleons might be finite even in a microscopic causal theory if the electromagnetic form factors vanish sufficiently rapidly at high momenta, as indicated by certain consistency requirements.[2] With this assumption Wick and Sorensen[3] have attempted a calculation of the nucleon mass difference on the basis of a formalism developed by Low.[4] Their calculation yields a negative result, giving a proton heavier than the neutron. No direct comparison can, however, be made between the two calculations. In FS the relativistic Born approximation to the self-energy is used, while WS are essentially led to a Born approximation formula with form factors, in which only positive-energy states are kept.

For this reason we have re-examined the problem by using as a basis the expression of the Compton scattering amplitude derived with a dispersion relation approach. The single-nucleon contribution is in our case simply the FS expression with their arbitrary cutoffs replaced by the electromagnetic form factors of the nucleons. We find that the mass difference that one obtains by extrapolating at high momenta the experimental form factors is wrong in sign and in magnitude. The reason is that the radii of the experimental distributions correspond to cutoffs considerably lower than those used in FS. We also find that the correct mass difference can be obtained, from the single-nucleon contribution and without contradicting the Stanford data, with a rather pathological neutron charge distribution, concentrated at small distances.[5] It may well be, on the other hand, that the main effect comes from the many-particle intermediate states.

We start, as in FS, with the expression:

$$\langle p'|S_2|p\rangle = -i\delta m(2\pi)^4\,\delta(p-p')\bar{u}(p')u(p) = \tfrac{1}{2}\delta(p-p')\int\frac{d^4k}{k^2-i\epsilon}\,\phi(k), \quad (1)$$

where

$$\phi(k) = i\int d^4x\, e^{ikx}\langle p|T(j_\mu(\tfrac{1}{2}x), j_\mu(-\tfrac{1}{2}x))|p\rangle, \quad (2)$$

with $j_\mu(x)$ the Heisenberg current operator. In-

stead of inserting directly in (2) a set of ingoing states in order to evaluate the current-ordered product, we consider the retarded amplitude for Compton scattering of virtual photons given by

$$M_{\mu\nu}=i\int d^4x\, e^{ikx}\langle p'|[j_\mu(\tfrac{1}{2}x),j_\nu(-\tfrac{1}{2}x)]|p\rangle\eta(-x), \quad (3)$$

from which $\phi(k)$ can be easily obtained. It is known from the work on Compton scattering of real photons[6] that one can write

$$M_{\mu\nu}=\sum_i \bar{u}(p')I_{\mu\nu}{}^{(i)}u(p)M^{(i)}(\nu,\Delta^2), \quad (4)$$

where $I_{\mu\nu}{}^{(i)}$ are a set of gauge-invariant tensors formed with the γ matrices and three of the four momenta involved, and Δ^2 the conventional invariant energy and momentum transfer.[7] From causality one has for the scalar amplitudes:

$$\mathrm{Re}\,M^{(i)}(\nu,\Delta^2)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{\mathrm{Im}\,M^{(i)}(\nu',\Delta^2)}{\nu-\nu'}\,d\nu'+P_n(\nu), \quad (5)$$

with $P_n(\nu)$ a polynomial in ν. There is one set $I_{\mu\nu}{}^{(i)}$ such that the single-nucleon contribution to $\mathrm{Im}M^{(i)}$ gives for $M^{(i)}$ the relativistic Born approximation for Compton scattering from nucleons with the experimental magnetic moments. For this choice there are reasons to believe[8] that the polynomial $P_n(\nu)$ is absent in (5).

We take the same attitude for virtual photons and use relations (5) without polynomial also in our case. Then, even without writing the invariants explicitly, we can immediately write the one-nucleon contribution M^N:

$$M_{\mu\nu}{}^N=\sum\left[\frac{\langle p'|j_\mu|P-k\rangle\langle P-k|j_\nu|p\rangle}{2M\nu+k^2-i\epsilon}+\frac{\langle p'|j_\nu|P+k\rangle\langle P+k|j_\mu|p\rangle}{-2M\nu+k^2+i\epsilon}\right], \quad (6)$$

where the sum is on the spins of the intermediate nucleon state. By using the well-known expressions for the matrix elements of the current,[9] one obtains

$$\phi^N(k)=\bar{u}(p)\left\{[eF_1(k^2)\gamma_\mu+i\mu F_2(k^2)\sigma_{\mu\lambda}k_\lambda]\frac{-i\gamma(p-k)+M}{-2pk+k^2}[eF_1(k^2)\gamma_\mu-i\mu F_2(k^2)\sigma_{\mu\nu}k_\nu]+(k\to -k)\right\}u(p). \quad (7)$$

Equation (7) gives for the self energy exactly the FS expression with their arbitrary cutoff functions replaced by the form factors $F_1(k^2)$, $F_2(k^2)$, while the calculation in (3) obtained for $\phi^N(k)$ an expression in which the invariant denominators of Eq. (7) were replaced by those corresponding to positive-energy intermediate states only.

If one uses for the form factors the exponentials suggested by the experimental data of Hofstadter,[10,11]

$$F_1{}^{(p)}(k^2)=F_2{}^{(p)}(k^2)=F_2{}^{(n)}(k^2)=\alpha^4/(\alpha^2+k^2)^2,$$
$$F_1{}^{(n)}(k^2)=0, \quad (8)$$

with $\alpha^2=37.5\mu^2$, the mass difference turns out to be

$$\Delta M=\delta m^{(n)}-\delta m^{(p)}=-0.30\,(1/137\pi)\,M=-0.66\ \mathrm{Mev},$$

instead of the experimental value $M_{\mathrm{exp}}=+1.2$ Mev. No possibility seems to exist of obtaining even the right sign of ΔM if one uses extrapolations to high values of k^2 with one-parameter functions determined from the experimental data at low values of k^2, even allowing for the experimental errors in the mean square radii.

If the bulk of the effect is to be explained by the single-nucleon term one must introduce form factors with important contributions from high mass values in the spectral function. Inserting the spectral representation for the form factors, one finds for the electromagnetic self-mass of a nucleon, neutron or proton (in units of the nucleon mass)

$$\delta m=\frac{1}{137\pi}[L_{11}-\tfrac{1}{2}\mu L_{12}-(\tfrac{1}{2}\mu)^2L_{22}], \quad (9)$$

where

$$L_{ij}=\pi^{-2}\int dm^2dm'^2(m^2-m'^2)^{-1}\times\rho_i(m^2)\rho_j(m'^2)[f_{ij}(m^2)-f_{ij}(m'^2)]. \quad (10)$$

μ is the nucleon anomalous magnetic moment and $\rho_1(m^2)$, $\rho_2(m^2)$ are the spectral functions for the charge and magnetic moment, respectively, as defined by Chew et al.,[12] and

$$f_{11}(m^2)=-\tfrac{1}{2}[\tfrac{1}{4}m^2\ln m^2+(1+\tfrac{1}{2}m^2)(4-m^2)w(m^2)],$$
$$f_{12}(m^2)=\tfrac{3}{2}[\tfrac{1}{2}m^2\ln m^2+m^2(4-m^2)\,w(m^2)],$$
$$f_{22}(m^2)=\tfrac{1}{4}[-\tfrac{1}{2}m^2+\tfrac{1}{2}m^2(3+\tfrac{1}{2}m^2)\ln m^2+(4+\tfrac{1}{2}m^2)m^2(4-m^2)w(m^2)],$$

with

$$w(m^2) = [m^2(4-m^2)]^{-1/2} \arctan [m^{-2}(4-m^2)]^{1/2} \quad \text{for } m^2<4$$

$$= [m^2(m^2-4)]^{-1/2} \ln \tfrac{1}{2}[m + (m^2-4)^{1/2}] \quad \text{for } m^2>4.$$

We have tried a model in which only the neutron charge spectral function has contributions from high mass values.[13] With $F_1^{(p)}$, $F_2^{(p)}$, and $F_2^{(n)}$ as in (8) and $F_1^{(n)}$ given by

$$F_1^{(n)}(k^2) = \epsilon\omega^4 k^2/(k^2+\omega^2)^2,$$

which corresponds to a charge distribution of the form $e^{-\omega r}/r - \frac{1}{2}\omega e^{-\omega r}$ and which is consistent with the Stanford data for $\epsilon \lesssim 2.2\times10^{-2} M^{-2}$, we find, for ϵ equal to its upper limit, the right ΔM for $\omega \approx 10M$. The high value of ω raises, however, the question of the importance of the many-particle states. Conversely, if many-particle states are important, it seems that they should also be important in the spectral representations of the form factors and again give rise to distributions highly concentrated at small distances.[14]

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[1]R. P. Feynman and G. Speisman, Phys. Rev. 94, 500 (1954) (referred to as FS in the following). See also A. Petermann, Helv. Phys. Acta 27, 441 (1954); K. Huang, Phys. Rev. 101, 1173 (1956).

[2]Lehmann, Symanzik, and Zimmermann, Nuovo cimento 2, 425 (1955).

[3]G. C. Wick, Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957 (Interscience Publishers, New York, 1957), Chap. I, p. 41; R. A. Sorensen, Atomic Energy Commission Report NYO-7119 (unpublished). (Both papers are referred to as WS.)

[4]F. Low, Phys. Rev. 97, 1992 (1955).

[5]A calculation of the mass difference of the pions has been done by Riazzuddin (Phys. Rev. Lett. to be published). In his case the electromagnetic structure of the pions is not known and he derives a mean square radius from the mass difference. If, however, a strong pion-pion interaction exists, for which there seems to be some indication, the actual mean square radius will be larger than the one found from the mass difference and the situation would be quite similar to the nucleon case.

[6]N. N. Bogoliubov and D. V. Shirkov, Doklady Akad. Nauk S.S.S.R. 113, 529 (1957); R. E. Prange, Phys. Rev. 110, 240 (1958).

[7]$\nu = -(Pk)/M$; $P = \frac{1}{2}(p+p')$; $\Delta^2 = (p-p')^2$.

[8]M. Gell-Mann and J. Mathews, in 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 98.

[9]G. Salzman, Phys. Rev. 99, 973 (1953).

[10]R. Hofstadter, in 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 11 ff.

[11]In our calculation also time-like k^2 occurs while the experimental results refer only to space-like k^2. The usual Feynman technique of integration takes care of this.

[12]Chew, Gasiorowicz, Karplus, and Zachariasen, Phys. Rev. 110, 265 (1958); Federbush, Goldberger, and Treiman, Phys. Rev. 112, 642 (1958).

[13]L. I. Schiff [1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 14] has proposed for $F_1^{(n)}$ a function different from zero at large k^2 consistent with all the low-momenta data; since, however, it does not vanish for $k^2 \to \infty$ it cannot give a finite electromagnetic self-mass.

[14]As to the importance of the one-meson contribution it may be relevant to note that by extrapolating the approximate expression for the amplitude of meson electroproduction given by Fubini, Nambu, and Wataghin [Phys. Rev. 111, 329 (1958)], stated to be reliable up to $k^2 \approx 0.3M^2$, the effect of the $\frac{3}{2}$, $\frac{3}{2}$ resonant state drops out, and the contribution will be negligible.

ELECTRON-NEUTRINO ANGULAR CORRELATION IN THE BETA DECAY OF NEON-23*

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The electron-neutrino angular correlation coefficient for the beta decay of Ne^{23} as measured by Ridley[1] represents the most serious experimental disagreement with the presently accepted vector and axial-vector interpretation of beta decay. On the assumption that the decay of Ne^{23} is a Gamow-Teller transition, the angular correlation coefficient λ will be $+\frac{1}{3}$ or $-\frac{1}{3}$ corresponding, respectively, to the tensor or axial-vector interactions. Ridley obtained the value $\lambda = -0.05 \pm 0.10$ which implies a mixture of T and A in comparable strength. We have re-evaluated the angular correlation coefficient in the decay of Ne^{23} using the same technique previously employed[2-4] to measure the angular correlations of Ne^{19}, A^{35}, and He^6. Our experimental result, $\lambda = -0.37 \pm 0.04$, indicates that the axial-vector in-

teraction is dominant in the Gamow-Teller type of decay.

Ne^{23} decays[5] by electron emission with about 99% of the transitions going to the ground and first excited states of Na^{23}. The maximum electron energies and branching ratios of the transitions to the ground and first excited state are 4.39 Mev (67 ± 3%) and 3.95 Mev (32 ± 3%), respectively. The decay to the first excited state is followed by the emission of a single 436-kev gamma ray. The beta decay is an allowed one: the decay to the ground state is a pure G-T transition ($\Delta I = 1$, no change in parity) while the decay to the first excited state would allow a mixture of Fermi and G-T transitions ($\Delta I = 0$, no change in parity). However, theoretical considerations predict that a change of isotopic spin accompanies the decay to the first excited state resulting in a strong predominance of the G-T decay.[1] In the analysis of this experiment, the transition to the first excited state was therefore assumed to be pure G-T. The very weak transitions to higher levels were neglected.

The Ne^{23} was produced by the reaction $Na^{23}(n, p)Ne^{23}$. About 300 grams of finely powdered Na_2CO_3 were exposed to the fast neutron flux inside a fuel thimble in the *CP*-5 reactor at Argonne National Laboratory. The arrangement for sweeping out and purifying the gas was identical with that used in the He^6 experiment.[4] The purity of the activity was tested by measuring the half-life. A single activity was observed with a half-life of 37.5 ± 0.1 sec, in good agreement with the value 37.6 ± 0.1 sec found[5] by Penning and Schmidt for Ne^{23}.

The angular correlation coefficient λ was deduced from the measured energy distribution of the recoil ions. The recoil energy was selected by two spherical electrostatic spectrometers in series and the ions were detected by a conventional Allen-type electron multiplier. The experimental results and the theoretically predicted spectra for various values of λ are shown in Fig. 1. The energy spectrum of the recoil ions was taken as a composite of the individual spectra of the transitions to the ground and first excited state of Na^{23}. The theoretical curves include the Coulomb effect of the nuclear charge and have been corrected for the gamma ray following the decay to the first excited state and for the finite energy resolution of the spectrometers. Each experimental point represents about 50 000 true recoil counts with an error of about 800 counts. The point on the steep right side of

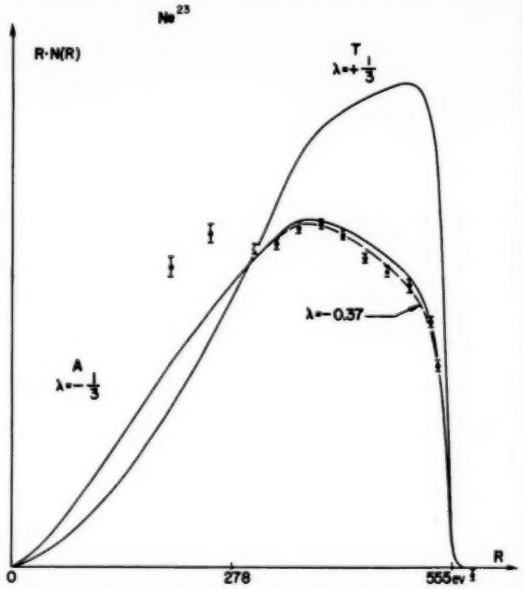

FIG. 1. The distribution of recoil ions observed in the decay of Ne^{23} plotted as a function of the recoil energy R. The solid curves are the computed distributions for the tensor (T) and axial-vector (A) interactions. Since the transmission of the spectrometer is proportional to the recoil energy, the probability function $N(R)$ is shown multiplied by R. The dotted curve represents the best fit to the data. The experimental points below 278 ev include multiply-charged ions.

the spectrum was used to calibrate the energy scale of the spectrometer relative to the theoretical maximum recoil energy. The abrupt rise in the spectrum shown by the two experimental points below 278 ev is caused by the presence of multiply-charged recoil ions, since the electrostatic spectrometers will transmit a doubly-charged ion of a given energy at a voltage setting corresponding to a singly-charged ion of one-half that energy. Since the proportion of such ions is unknown, these points were neglected in the calculation of λ.

A least-squares analysis of the data at the nine points on the spectrum between 300 ev and 530 ev yields the experimental value of $\lambda = -0.37 \pm 0.04$. The error quoted is a statistical error; no allowance has been made for possible systematic experimental errors. An uncertainty of the same size is introduced by the uncertainty (3%) in the branching ratios of the Ne^{23} decay.

Our results, then, supply additional evidence that the G-T transition is axial-vector. The results also verify the initial assumption that the

decay to the first excited state of Na^{23} is predominantly G-T since, if one accepts the Fermi transition as vector,[2] any admixture of a Fermi transition would lead to a less negative value of λ than $-\frac{1}{3}$.

*Work performed under the auspices of the U. S. Atomic Energy Commission and also supported in part by the Office of Naval Research.

†Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[1]B. W. Ridley, Nuclear Phys. 6, 34 (1958).

[2]Herrmannsfeldt, Maxson, Stähelin, and Allen, Phys. Rev. 107, 641 (1957).

[3]Herrmannsfeldt, Stähelin, and Allen, Bull. Am. Phys. Soc. Ser. II, 3, 52 (1958).

[4]Herrmannsfeldt, Burman, Stähelin, Allen, and Braid, Phys. Rev. Lett. 1, 61 (1958).

[5]J. R. Penning and F. H. Schmidt, Phys. Rev. 105, 647 (1957).

FURTHER SEARCH FOR PARITY NONCONSERVATION IN ASSOCIATED PRODUCTION*

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Several authors have pointed out that the case for parity conservation in strong interactions is very much weakened when strange particles are involved.[1,2] If parity is not conserved in the associated production process

$$\pi^- + p \rightarrow \Lambda + K^0, \qquad (1)$$

then the Λ may have a polarization component in the production plane. The parity-nonconserving decay

$$\Lambda \rightarrow p + \pi^- \qquad (2)$$

may then, by virtue of its large decay-asymmetry parameter, exhibit a decay asymmetry in the production plane.

In an earlier Letter we reported our analysis of 236 events of the type (1)+(2), produced by 1.12-Bev/c pions incident upon a liquid hydrogen bubble chamber, leading to Λ's of 300 Mev/c c.m. momentum.[3] Those results were consistent with zero decay asymmetry in the production plane. We now report our analysis of 185 events of the same type, but produced at a higher energy by pions of 1.23 Bev/c, leading to 375-Mev/c Λ's in the c.m. system.

One might expect from statistical considerations that adding 185 events to an existing 236 could hardly change the conclusions. However, (a) it turns out that, partly because of a larger observed up-down decay asymmetry, and partly because of a smaller observed decay asymmetry in the production plane, we can set a substantially smaller limit (about one-third as large) to the amount of parity-nonconserving amplitude in the experiment reported here than in the 1.12-Bev/c experiment; and (b) it is conceivable that a parity-nonconserving production amplitude could increase substantially between 300 and 375 Mev/c.

Figure 1 shows the observed decay-asymmetry components in the production plane plotted against θ, the hyperon c.m. production angle. In the left half of the figure we plot the front-back (FB) asymmetry in the π-c.m. coordinate system, in which the positive direction is along $\vec{P}$ (π incident). The right half of the figure shows the left-right (LR) asymmetry in the same system. The positive direction is along $\vec{n}\times\vec{P}$ (π inc), where $\vec{n}$ is the "up" direction given by $\vec{P}(\pi \text{ inc})\times\vec{P}$ (hyperon). All directions are as seen in the hyperon rest frame. These data are clearly consistent with zero asymmetry. A χ^2 test applied to the hypothesis that the FB asymmetry is everywhere zero yields $\chi^2(\text{FB}) = 7.3$, where 6 is "expected." Similarly $\chi^2(\text{LR}) = 1.0$. These combine to give a total $\chi^2 = 8.3$, where 12 is expected if the asymmetry is identically zero. This corresponds to a χ^2 probability of 76%.

The contribution to χ^2 at each value of θ is just the square of the magnitude of the projection of

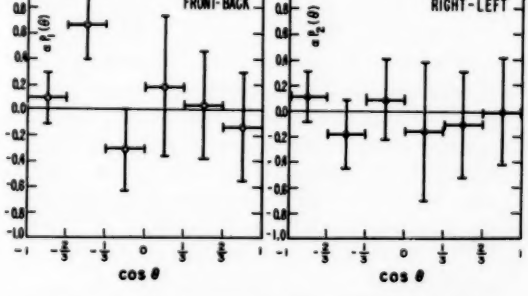

FIG. 1. Decay asymmetry components in the production plane (see text).

the observed decay-asymmetry vector on the production plane, in units of the mean-square statistical error. It is therefore invariant under rotation to a new "preferred axis" in the production plane. The same is true after summing over θ. Therefore zero asymmetry in the production plane fits with 76% probability in any coordinate system.

If we average each component of the asymmetry vector over θ, the result depends on the choice of preferred axis. (The above analysis shows that the result may in any case be consistent with zero.) We make three choices of preferred axes: the π-c.m. system (defined above), and the Λ-c.m. and Λ-lab systems (defined in reference 3). We find

$$(\alpha\bar{P}_1, \alpha\bar{P}_2)_{\pi\text{-c.m.}} = (0.14 \pm 0.13, -0.002 \pm 0.13), \quad (3)$$

$$(\alpha\bar{P}_1, \alpha\bar{P}_2)_{\Lambda\text{-c.m.}} = (-0.10 \pm 0.13, -0.16 \pm 0.13), \quad (4)$$

$$(\alpha\bar{P}_1, \alpha\bar{P}_2)_{\Lambda\text{-lab}} = (0.12 \pm 0.13, -0.09 \pm 0.13), \quad (5)$$

The up-down asymmetry, which demonstrates parity nonconservation in the decay (2), is naturally the same in all three systems and is given by

$$\alpha\bar{P}_n = 0.66 \pm 0.13. \quad (6)$$

We can adopt the hypothesis that parity is not conserved in Reaction (1), in order to obtain a rough upper limit to the parity-nonconserving amplitude. The possibility of obtaining such an upper limit arises from the large observed up-down asymmetry (6). An analysis (confined to s and p waves) yields for F, the fractional intensity of parity-nonconserving production,

$$F = 0.58(\alpha\bar{P}_1)^2 + 0.60(\alpha\bar{P}_2)^2 + 0.62\alpha\bar{P}_1\alpha\bar{P}_2, \quad (7)$$

where P_1 and P_2 refer to the π-c.m. system.[2-4] If $\alpha\bar{P}_1$ and $\alpha\bar{P}_2$ are assumed to be independently Gaussian-distributed, with expectation values and standard deviations given by the results (3), we can calculate the probability distribution in F by changing variables and performing one integration. The result can be represented empirically by $P(F)dF = 39\exp(-48F)dF$, for $0 \leq F \leq 0.015$, and $P(F)dF = 27\exp(-30F)$, for $0.015 \leq F$. Thus $F = 0$ is most likely, $\langle F\rangle = 0.029$, $(\langle F^2\rangle - \langle F\rangle^2)^{1/2} = 0.035$, and Prob. $(F > F_0)$ is roughly $0.9 \times \exp(-30\,F_0)$.[5]

We are grateful to Luis W. Alvarez for his support and guidance in this work.

*This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1]G. Feinberg, Phys. Rev. 108, 878 (1957); V. G. Soloviev, Nuclear Phys. 6, 618 (1958).

[2]Drell, Frautschi, and Lockett, Stanford University Physics Department, Technical Report No. 30, June, 1958 (unpublished).

[3]Crawford, Cresti, Good, Solmitz, and Stevenson, Phys. Rev. Lett. 1, 209 (1958). Notation, details of the analysis suggested by Drell et al., further discussion, and references to other work may be found there.

[4]The analysis uses production and decay angular-distribution results at 1.23 Bev/c (to be published). The solutions depend only very weakly on the value of α, in the experimentally allowed region $0.8 < \alpha < 1.0$. There is no evidence for d waves.

[5]In reference 3 we obtained $F = 0.07 \pm 0.08$ by erroneously applying ordinary methods of differential "error propagation" to an expression analogous to Eq. (7). This procedure is clearly incorrect for a quadratic centered near the origin, since the second-order terms are then dominant rather than negligible. Our result $F(1.12\ \text{Bev}/c) = 1.15(\alpha\bar{P}_1)^2 + 0.93(\alpha\bar{P}_2)^2 - 1.44\alpha\bar{P}_1\alpha\bar{P}_2$, leads to a probability distribution $P(F)dF \approx 10\exp(-10F) \times dF$, so that $F = 0$ is most likely, $\langle F\rangle = 0.10$, $(\langle F^2\rangle - \langle F\rangle^2)^{1/2} = 0.10$, and Prob. $(F > F_0) = \exp(-10F_0)$.

ISOTOPIC SPIN SELECTION RULES AND K_2^0 DECAY*

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(Received December 1, 1958)

One of the interesting theoretical points connected with the decays of the strange particles is to determine whether there exists some kind of isotopic spin selection rule for these decays or not. Currently, there are two main view points on this issue. In the first point of view, one chooses the interaction Hamiltonian responsible for the weak decays to obey the familiar $\Delta I = \frac{1}{2}$ selection rule.[1] Though that rule was originally intended to apply for the nonleptonic modes, it may be extended to the leptonic modes also (if we assign zero isotopic spin for leptons). In the second point of view,[2] the weak interaction Hamiltonian is a current-current interaction and the interacting nonleptonic currents are taken to have definite transformation properties: the

strangeness-conserving current transforms as an isovector and the strangeness-violating current transforms as an isospinor. For simplicity we call this the "$I=\frac{1}{2}$ current" rule. Both the extended $\Delta I=\frac{1}{2}$ selection rule and the $I=\frac{1}{2}$ current rule predict the same results for leptonic decays. However, for the nonleptonic decays of the strange particles, the $I=\frac{1}{2}$ current rule gives a $\Delta I=\frac{3}{2}$ component in the Hamiltonian as well as a $\Delta I=\frac{1}{2}$ component. Thus, generally, the two rules will make different predictions for these decays and there seems to be no way to make an experimental[3] choice between them at the present time. However, we note that if we believe in the present ansatz of charged current-current couplings generating weak interaction, the second viewpoint will be theoretically favored, since the over-all $\Delta I=\frac{1}{2}$ rule requires neutral current-current couplings also.

In the present note, we show that if the extended $\Delta I=\frac{1}{2}$ selection rule is true for both leptonic and nonleptonic modes, then we can calculate almost uniquely the lifetime of K_2^0 and the various branching ratios of K_2^0 decay from the known decay rates of K^+ decay. Unfortunately, the present experimental results are not sufficiently accurate but we may hope to make this test more incisive in the near future. In what follows, we assume spin zero for the K meson and CP-invariance of the theory as well as the $\Delta I=\frac{1}{2}$ rule. We can derive the following identity between the transition probabilities without much difficulty:[4,5]

$$w(K_2^0\to 3\pi)=w(K^+\to 3\pi). \tag{1}$$

Furthermore, in a previous note,[2] we proved the relations

$$w(K_2^0\to\pi^\pm+e^\mp\mp\nu)=2w(K^+\to\pi^0+e^++\nu),$$
$$w(K_2^0\to\pi^\pm+\mu^\mp\mp\nu)=2w(K^+\to\pi^0+\mu^++\nu). \tag{2}$$

Since these are the major decay modes of K_2^0, we can immediately calculate the lifetime of K_2^0 and various branching ratios from the known data for K^+ decay.[6] The result is

$$\tau_{\text{theoretical}}(K_2^0)=5.16\times10^{-8}\,\text{sec}, \tag{3}$$

which must be compared with the experimental value[7]

$$\tau_{\text{experimental}}(K_2^0)=(9.0_{-2.5}^{+3.5})\times10^{-8}\,\text{sec}. \tag{4}$$

The calculated branching ratios are

$$K_2^0\to\pi^-+\mu^++\nu, \quad 0.17$$
$$K_2^0\to\pi^++\mu^-+\bar{\nu}, \quad 0.17$$
$$K_2^0\to\pi^-+e^++\nu, \quad 0.18$$
$$K_2^0\to\pi^++e^-+\bar{\nu}, \quad 0.18$$
$$K_2^0\to 3\pi, \quad 0.30. \tag{5}$$

Furthermore, if we make the assumption that the final state in 3-pion decay is completely symmetric with respect to the space wave functions of the pions, which is approximately justified by the experimental results, then[8]

$$\frac{w(K_2^0\to\pi^0+\pi^0+\pi^0)}{w(K_2^0\to\pi^++\pi^-+\pi^0)}=\frac{3}{2}. \tag{6}$$

Then, the branching ratios for $K_2^0\to 3\pi$ is further subdivided to give

$$K_2^0\to\pi^++\pi^-+\pi^0, \quad 0.12$$
$$K_2^0\to\pi^0+\pi^0+\pi^0, \quad 0.18. \tag{7}$$

Thus, there is some discrepancy between the calculated and experimental lifetimes [Eqs. (3) and (4)]. If we take this seriously, then we must discredit Eq. (1) and/or Eq. (2), namely the extended $\Delta I=\frac{1}{2}$ selection rule for K_2^0 decay.

Suppose that for a moment we take the first point of view, so that we discard the $I=\frac{1}{2}$ current rule for the leptonic modes and believe in the restricted $\Delta I=\frac{1}{2}$ rule, (i.e., for nonleptonic modes only). Then, Eq. (1) will still hold and presumably Eq. (6), also. Then, we can still calculate the absolute transition rate

$$w(K_2^0\to\pi^++\pi^-+\pi^0)=2.4\times10^6\,\text{sec}^{-1}.$$

On the other hand, the experimental upper limit[9] to the charged three-pion mode is ~14% and using the experimental lifetime [see Eq. (4)], we get

$$2.1\times10^8\,\text{sec}^{-1}\gg w(K_2^0\to\pi^++\pi^-+\pi^0).$$

This is at variance with the calculated value given above. This could be an argument against the $\Delta I=\frac{1}{2}$ rule for nonleptonic modes.[10] However, the experimental values quoted above do not appear very reliable and it is desirable to have more accurate measurements. Furthermore, the calculated value, Eq. (3), may increase by as much as 20%, if we use different data[11] for the relative abundance of the $K_{\mu3}$ and K_{e3} modes of the positive K meson. For these reasons, it seems too early to discredit the $\Delta I=\frac{1}{2}$ rule.

Next, we would like to comment on the $I=\frac{1}{2}$ current rule. In this case, we have both $\Delta I=\frac{1}{2}$ and $\Delta I=\frac{3}{2}$ for the nonleptonic modes, and as a result, we no longer have relations like Eq. (1); but we still have Eq. (2). Consequently, we cannot calculate the absolute lifetime of K_2^0 as Eq. (3), but only an upper limit, which was the result of the previous paper.[2] In this case, however, instead of Eq. (6), we have[12]

$$0 \leq \frac{w(K_2^0 \to \pi^0+\pi^0+\pi^0)}{w(K_2^0 \to \pi^++\pi^-+\pi^0)} \leq \tfrac{3}{2}. \qquad (8)$$

If the final 3-pion space wave function is completely symmetric, we will have Eq. (6) again.

Finally, it is worthwhile to observe that $K_1^0 \to 3\pi^0$ (not $K_2^0 \to 3\pi^0$) is absolutely forbidden, independent of isotopic spin selection rules, if CP-invariance holds.[13,14] This could be checked experimentally. Furthermore, $K_1^0 \to \pi^+ + \pi^- + \pi^0$ (again not K_2^0) will be forbidden, provided the final 3-pion space wave function is completely symmetric. This conclusion is again independent of the $\Delta I=\frac{1}{2}$ rule.[13,14] Thus, its presence will give a proof of the existence of a nonsymmetrical space wave function for the 3-pion final state in the decay.

We wish to thank Professor R. H. Dalitz for an interesting discussion of some of these points.

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*Assisted in part by the U. S. Atomic Energy Commission.

[1]For a review of this subject, see: M. Gell-Mann and A. H. Rosenfeld, Annual Review of Nuclear Science (Annual Reviews, Inc., Stanford, 1957), Vol. 7.

[2]Okubo, Marshak, Sudarshan, Teutsch, and Weinberg, Phys. Rev. 112, 665 (1958). L. B. Okun, Proceedings of the Padua-Venice Conference on Mesons and Newly Discovered Particles, 1957 (to be published).

[3]For the case of Λ-decay, see Okubo, Marshak, and Sudarshan, Phys. Rev. (to be published).

[4]This can be derived by slightly modifying the discussion by Dalitz: R. H. Dalitz, Reports on Progress in Physics (The Physical Society, London, 1957), Vol. XX, p. 163.

[5]M. Gell-Mann and A. H. Rosenfeld, Annual Review of Nuclear Science (Annual Reviews, Inc., Stanford, 1957), Vol. 7, p. 464. However, we are not necessarily to assume the complete symmetry of the final 3-pion states, as it seems to be stated there.

[6]We used the data for K^+ given by Gell-Mann and Rosenfeld (see reference 1.).

[7]M. Bardon et al., Phys. Rev. 110, 780 (1958).

[8]This was also derived by Gell-Mann and Rosenfeld (see reference 5).

[9]L. M. Lederman: quoted by R. H. Dalitz, Reference 10.

[10]A similar argument was given by R. H. Dalitz at the Conference on Weak Interactions, Gatlinburg, Tennessee, October, 1958 (unpublished).

[11]R. W. Birge et al., Nuovo cimento 4, 834 (1956).

[12]We used the method of Dalitz: R. H. Dalitz, Proc. Phys. Soc. (London) A69, 527 (1956).

[13]The state of zero charge and total isotopic spin I of N pions is identically an eigenstate of the charge conjugation operator with eigenvalue $(-1)^{I+N}$. So, if the K meson has zero spin and CP-invariance holds, the final three-pion state in the decay of K_1^0 (K_2^0) must have even (odd) isotopic spin. Since symmetric isotopic spin wave functions of 3 pions are possible only for odd isotopic spin ($I=1$ or $I=3$), the final space wave function for $K_1 \to 3\pi$ must automatically be unsymmetric.

[14]Note added in proof: It has been called to our attention that these conclusions have been stated also by A. Pais and S. B. Treiman, Phys. Rev. 106, 1106 (1957).

ERRATA

OPTICAL MODEL OF INELASTIC SCATTERING. T. K. Fowler [Phys. Rev. Lett. 1, 371 (1958).

The left-hand side of Eq. (7) should read λ instead of γ.

SHOCK-WAVE COMPRESSION OF ALUMINUM. D. G. Doran, G. R. Fowles, and G. A. Peterson [Phys. Rev. Lett. 1, 402 (1958)].

The authors failed to note that the use of reflected light with aluminized Mylar to indicate shock arrival times had been described previously in a document by J. M. Majowicz and S. J. Jacobs of the Explosions Research Department of the U. S. Naval Ordnance Laboratory [NAVORD Report 5710 (unpublished)].

ABSTRACTS

In this section are printed the abstracts of Articles that have been forwarded to The American Institute of Physics for publication in THE PHYSICAL REVIEW. In quoting information obtained from this section before the appearance of the corresponding Article, reference should be made to "Physical Review (to be published)" rather than to this Journal.

CONDUCTIVITY OF PLASMAS TO MICROWAVES. P. H. Fang, National Bureau of Standards, Washington, D. C. (Received September 2, 1958).

Plasma conductivities for electrons with Maxwellian energy distribution are evaluated for the cases in which the collision cross section is (i) velocity independent and (ii) inversely proportional to the velocity. The corresponding distribution functions of relaxation times are discussed.

MEASUREMENTS OF DISSOCIATIVE RECOMBINATION AND DIFFUSION IN NITROGEN AT LOW PRESSURES. A. C. Faire and K. S. W. Champion,* Geophysics Research Directorate, Air Force Cambridge Research Center, Laurence G. Hanscom Field, Bedford, Massachusetts (Received January 2, 1958; revised manuscript received June 23, 1958).

The measurements of recombination in nitrogen and nitrogen-helium mixtures by Faire, Fundingsland, Aden, and Champion have been extended using, in addition to the basic microwave techniques, a monochromator and photomultiplier to study the spectra emitted. Electron production in the afterglow due to helium metastables has been investigated and the results have made it possible to correct, where necessary, the apparent value of the recombination coefficient of nitrogen ions in nitrogen-helium mixtures. In addition, the ambipolar diffusion coefficient in nitrogen has been measured. This has been used to correct for losses due to fundamental-mode diffusion. The magnitude of higher-mode diffusion losses is discussed and shown to be small in this experiment.

The average values of the recombination and diffusion coefficients determined by this experiment are, respectively,

$$\alpha = (4.0 \pm 0.3) \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1},$$
$$D_a p = 220 \pm 30 \text{ cm}^2 \text{ sec}^{-1} \text{ mm Hg},$$

with an electron temperature of approximately 400°K. For pressures below 4 mm Hg it was found that the value of α was independent of pressure.

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SIGNIFICANCE OF FORMATIVE TIME LAGS IN GASEOUS BREAKDOWN. Leonard B. Loeb, Department of Physics, University of California, Berkeley, California (Received August 27, 1958).

Delineating formative time lag studies of gaseous breakdown as conventionally carried out, this type of investigation is analyzed as it applies to two breakdown types. These are (1) the breakdown thresholds set by the generic Townsend relation, in many instances difficult to detect, but for which time scales observed delineate the well-established atom physical mechanisms active; (2) the more dramatic transient spark-like breakdowns, involving appearance of negative resistance characteristics caused by alterations of the gas, the electrodes, or space charge disposition of an unpredictable character. On this basis, the various breakdown phenomena known are listed and characterized as to their amenability to profitable time lag studies. It is further indicated that in contrast to time lag studies, the fast oscilloscopic analysis of breakdowns delineating transient current, potential, and luminosity as a function of space and time can prove invaluable, and areas requiring this type of analysis are indicated.

ZEEMAN-TYPE MAGNETO-OPTICAL STUDIES OF INTERBAND TRANSITIONS IN SEMICONDUCTORS. E. Burstein,* G. S. Picus, R. F. Wallis, and F. Blatt,† U. S. Naval Research Laboratory, Washington, D. C. (Received July 31, 1958).

In the presence of a magnetic field the quasi-continuous levels of simple energy bands are coalesced into one-dimensional sub-bands and the "time reversal" degeneracy of the levels is split. The energy levels are characterized by the quantum numbers $\hbar k_H$, the crystal momentum along the magnetic field direction; l, the Landau magnetic quantum number; and M, the component of the total angular momentum along the magnetic field which is characteristic of the atomic states in the tight binding limit. In the

case of degenerate valence bands, the effect of a magnetic field is complicated by degeneracy effects and the levels in a magnetic field are characterized by two or more pairs of (l, M) values. The selection rules, polarization effects, and the character of the absorption spectra for interband transitions in the presence of a magnetic field are discussed and illustrated by experimental data for Ge and InSb. A discussion of practical and experimental considerations of Zeeman-type interband magneto-optical effects is also presented.

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LENGTH AND RESISTIVITY CHANGES IN GERMANIUM UPON LOW-TEMPERATURE DEUTERON IRRADIATION AND ANNEALING. Frederick L. Vook* and R. W. Balluffi, University of Illinois, Urbana, Illinois (Received August 19, 1958).

Simultaneous measurements of the length change and resistivity of high-purity germanium single crystals were made upon irradiation and annealing. The specimens were initially irradiated at 25°K with deuterons of average energy 10.2 Mev to an integrated flux of 6.2×10^{16} deuterons/cm^2 and annealed to room temperature. The specimens were then irradiated at 85°K to an additional flux of 9.2×10^{16} deuterons/cm^2 and annealed to 364°K. The specific length expansion for both bombardments was $\Delta L/L=(1.5\pm0.3)\times10^{-21}$/(deuteron/cm^2). The annealing after both irradiations showed a gradual recovery of the expansion which was observable only after warming to above 200°K. The precise determination of the onset of annealing was limited by the accuracy of the expansion measurements (~20%). Recovery was ~50% complete by 300°K and ~85% complete by 360°K. The resistivity measurements agreed generally with previous results. A large increase in resistivity occurred during the low-temperature bombardments. The specimens became p-type after bombardment and annealing. On the first warmup after the bombardment at 25°K the resistivity decreased irreversibly by a factor of 10^6 between 65°K and 300°K with a large part of the decrease coming apparently between 150°K and 225°K. On the warmup from the second bombardment at 85°K an irreversible resistivity increase occurred on warming to 140°K. The resistivity then decreased irreversibly by a factor of 10^3 between 150°K and 200°K. Extensive resistivity annealing, therefore, occurred in an earlier stage of the recovery process than did the experimentally observable length-change annealing.

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LATTICE PARAMETER CHANGES IN DEUTERON-IRRADIATED GERMANIUM. R. O. Simmons, University of Illinois, Urbana, Illinois (Received August 19, 1958).

A lattice expansion of 3×10^{-5} was measured in germanium irradiated by 1.5×10^{17} 9-Mev deuterons/cm^2 at low temperature and annealed to 320°K. Thus residual specimen length expansion (as measured by Vook and Balluffi in similar samples) and lattice parameter expansion are small and nearly equal after annealing to room temperature. Thermal recovery to 380°K occurred parallel to that of macroscopic length changes, but near 380°K the (211) interplanar spacing had contracted about 3×10^{-5} relative to unirradiated crystal. The lattice parameter returned to that of unirradiated crystal at 430°K. No appreciable diffraction line broadening was observed. These results provide confirmatory evidence that structural damage in deuteron-irradiated germanium consists of well-localized centers of dilatation.

STRUCTURE OF DEUTERON-IRRADIATED GERMANIUM. Frederick L. Vook* and R. W. Balluffi, University of Illinois, Urbana, Illinois (Received August 19, 1958).

The structure of deuteron-irradiated germanium is discussed in the light of the following recent experiments: (1) simultaneous measurements of the change in length and resistivity upon low-temperature bombardment and annealing, (2) measurement of lattice parameter changes after annealing near room temperature, and (3) low-angle x-ray scattering measurements at liquid nitrogen temperature and above. A model of the damage at liquid nitrogen temperature, consisting of separated clusters of vacancies and interstitials, is proposed. The model yields a comparatively small length increase and fairly strong low-angle x-ray scattering in agreement with experiment. The model also appears capable of explaining the experimental

observation that resistivity annealing occurs in an earlier stage of the recovery process than appreciable length-change annealing. The clusters must be formed, at or below liquid nitrogen temperature, either by diffusive motion of the defects or by displacement processes directly upon bombardment. If the latter mechanism holds, present theory greatly underestimates displacement distances in germanium. Additional critical experiments are proposed.

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RADIATION DAMAGE EFFECTS ON FERROELECTRIC TRIGLYCINE SULFATE. A. G. Chynoweth, Bell Telephone Laboratories, Murray Hill, New Jersey (Received August 18, 1958).

Peculiar changes in the ferroelectric hysteresis loops of single cyrstals of triglycine sulfate result when the crystals are subjected to ionizing radiations (x-rays and electrons). Fully polarized crystals develop hysteresis loops biased along the field axis while partially polarized crystals develop double loop patterns, each subsidiary loop being biased to the same extent but in opposite directions. The biased loops retain their rectangularity during the early stages of the bombardment. The bias field builds up steadily during the bombardment while the reversible polarization shows no change at first but eventually, at a fairly well-defined value of the bias field, it begins to decay in a fairly rapid manner.

Unusual field- and temperature-dependent changes in the shapes of the "damaged" hysteresis loops are observed. Under certain conditions, a double loop pattern will "anneal" into a normal single loop simply as a result of applying the ac field; but when the field is removed, the crystal relaxes back to its double-loop form. Such cycles can be repeated, apparently indefinitely, provided that the field is not removed for too long a period. If this happens, the double-loop pattern fails to respond to further field treatments though it can be returned to the more unstable state by gentle heat treatment of the crystal.

The experiments rule out explanation of the effects based on the setting up of space charge fields or on nonuniform damaging of the crystal. It seems most likely that the effects are caused by the gradual building up of a more or less uniform strain in the crystal. The results are discussed in terms of the conventional double minimum potential energy curve used for describing ferroelectric mechanisms. On the basis of some pyroelectric studies, however, it appears that a rather more complicated potential energy curve is needed to describe ferroelectricity in triglycine sulfate.

It is pointed out that, as the x-ray dosages required to produce large changes in the ferroelectric properties are small compared with those usually used in crystallographic structure determination, it seems most unlikely that the structure of an undamaged triglycine sulfate crystal has yet been determined, and one wonders how true this may be of certain other structure determinations for radiation-sensitive organic crystals.

VIBRATION SPECTRA AND SPECIFIC HEATS OF DIAMOND-TYPE LATTICES. James C. Phillips,* Bell Telephone Laboratories, Murray Hill, New Jersey (Received July 14, 1958; revised manuscript received October 7, 1958).

A method is presented for calculating the frequency distribution of a crystal from measured dispersion curves without constructing a force constant model. The method is then used to compute a vibration spectrum for Ge based on elastic constants plus the dispersion curves measured by slow-neutron scattering. The vibration spectrum is used to calculate the lattice specific heat, the results agreeing with experiment to within a few percent. A slightly modified distribution yields results agreeing to within one percent. The results are sufficiently detailed to show the necessity for including corrections due to anharmonicity even at $T \sim \theta/2$. By analogy with the results for Ge, a vibration spectrum is constructed for grey tin that also gives good agreement with the specific heat measurements; from the spectrum and also by analogy with Ge, the dispersion curves for grey tin can be sketched. A similar discussion is also given for InSb and diamond.

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SPECIFIC HEAT OF GERMANIUM AND SILICON AT LOW TEMPERATURES. P. H. Keesom and G. Seidel,* Department of Physics, Purdue University, Lafayette, Indiana (Received August 21, 1958).

The specific heats of several samples of silicon have been measured between 1.2°K and 4.2°K.

The Debye characteristic temperature θ_0 at 0°K is estimated to be 636°K, a value slightly lower than previously reported. Measurements of germanium between 0.5°K and 4.2°K yield θ_0 = 363°K, in very good agreement with older results.

From knowledge of the electronic specific heat and the carrier concentration of several degenerate samples of germanium and silicon, information is deduced concerning the energy band structure of the crystals. Measurements of n-type germanium indicate that the conduction band of this substance has four minima. Similar measurements of silicon indicate that there are six minima in its conduction band. The density-of-states effective masses of both electrons and holes in germanium, calculated from this work on degenerate samples, are not appreciably different than found from cyclotron resonance experiments on pure crystals. This result is consistent with the assumption, used in the calculations, that the addition of impurities to a crystal does not change the density of states in the vicinity of the band edge. For silicon, however, the specific heat yields somewhat larger effective masses for the electrons and holes than obtained from cyclotron resonance. Thus, the addition of impurities to silicon affects the shape of the bands.

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EFFECT OF THE ENERGY GAP ON THE PENETRATION DEPTH OF SUPERCONDUCTORS.

A. L. Schawlow and G. E. Devlin, Bell Telephone Laboratories, Murray Hill, New Jersey (Received August 25, 1958).

The dependence on temperature of the penetration depth of superconducting tin crystals has been measured by a new low-frequency (100 kc/sec) method. The sample serves as the core of a solenoid whose inductance changes with the penetration depth. The inductance controls the frequency of an oscillator which can be measured precisely. It is found that there are departures from the law $\lambda=\lambda_0[1-(T/T_c)^4]^{1/2}$ derived from the Gorter-Casimir two-fluid theory. The departures are shown to arise from an energy gap in the spectrum of electron excitations and are qualitatively like those predicted by Lewis' extension of the two-fluid model to include a gap. Throughout the temperature range from 1.8°K to 3.69°K, the measured penetration depths agree well with the theory of Bardeen, Cooper, and Schrieffer.

ELASTIC CONSTANTS OF INDIUM ANTIMONIDE FROM 4.2°K TO 300°K.

L. J. Slutsky, Department of Chemistry, University of Texas, Austin, Texas, and C. W. Garland, Department of Chemistry and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts (Received September 11, 1958).

The adiabatic elastic constants of a single crystal of indium antimonide have been measured by an ultrasonic pulse technique in which 10-Mc/sec acoustic waves were employed. The elastic constants extrapolated to 0°K are, in units of 10^{12} dynes/cm^2, c_{11} = 0.6918, c_{12} = 0.3788, and c_{44} = 0.3132. A Debye characteristic temperature, θ, of 205° ± 2°K at 0°K was calculated from these values of the elastic constants.

LOW-TEMPERATURE LUMINESCENCE AND PHOTOCONDUCTIVITY OF AgCl.

Donald A. Wiegand,* Cornell University, Ithaca, New York (Received August 11, 1958).

The magnitudes and the decay processes of the luminescence and the photoconductivity of AgCl have been simultaneously investigated between 4°K and 210°K. The decrease of the luminescence intensity with increasing temperature can be attributed to a competing recombination process, not accompanied by visible radiation, and having a thermal activation energy of E = 0.05 ev. The decay times are not monotonic functions of temperature, but show maxima. These maxima can be explained in terms of a model in which energy is transported from the site of absorption to the luminescence center by mobile holes and electrons. Delay in this transport is caused by hole and electron trapping, and temperature dependence of the delay determines the temperature dependence of the decay times. Decay curves calculated on the basis of this model are in qualitative agreement with the observed data. The relative magnitudes of the luminescence and photocurrent decay times and the dependence of the decay and rise times on annealing indicate that if the major portion of the photoconductivity is due to electron motion, then luminescence occurs when holes are captured. It is suggested

that this recombination occurs at silver ion vacancies.

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EXCITON-INDUCED PHOTOEMISSION FROM BaO NEAR 80°K. E. Taft, H. Philipp, and L. Apker, General Electric Research Laboratory, Schenectady, New York (Received September 2, 1958).

This paper reports a new photoelectric study of BaO at 80°K. Special attention was devoted to the spectral region near $h\nu = 4$ ev, where Zollweg and Jahoda have found four peaks in the optical absorption. When BaO contains electron donor states lying less than 2 ev below the vacuum, these peaks show up clearly at 80°K in the spectral distribution of the photoelectric yield. The effect appears similar in character to exciton-induced photoemission from alkali halides. In BaO, the phenomenon furnishes a particularly sensitive means of studying the weak absorption peak at 3.8 ev, which can give rise to photoemission at photon energies as low as 3.3 ev. This is probably the source of the unexpected slow electrons previously observed by Philipp in energy distributions. Electron donor states giving rise to photoelectric thresholds as small as 0.8 ev were seen during the present studies.

CONFIGURATION COORDINATE MODEL FOR KCl:Tl INCLUDING SPIN-ORBIT INTERACTION. F. E. Williams and P. D. Johnson, General Electric Research Laboratory, Schenectady, New York (Received September 2, 1958).

The effect of the crystalline field on the spin-orbit interaction of the $^3P^\circ$ and $^1P^\circ$ states of Tl^+ in KCl has now been included in the configuration coordinate model. The potential energy curves for the pure spin states are required to satisfy the condition that after the application of spin-orbit interaction the resulting crystal states account for the absorption and emission spectra, explained by the earlier model, and for the oscillator strengths of the absorption bands. In accordance with the adiabatic approximation, the potential energy curves for the states involved in absorption and emission do not cross and the electronic matrix elements for radiative transitions depend on the configuration coordinate. The curve for the lower excited state has two minima which account for the 3050A and the 4750A emission bands. From the single minimum of the upper excited state, an additional emission band near the 2470A absorption band is predicted. With intense excitation at 77°K in a narrow spectral range near 1960A, which corresponds to excitation only to the upper excited state, the predicted emission has been found. The existence and characteristics of the new emission provide confirmation of the model, particularly of the quantitative effect of spin-orbit interaction.

THEORETICAL TOTAL-ENERGY DISTRIBUTION OF FIELD-EMITTED ELECTRONS. Russell D. Young, Field Emission Laboratory, The Pennsylvania State University, University Park, Pennsylvania (Received July 23, 1958).

The Fowler-Nordheim equation is derived in terms of total electron energy so as to obtain the total-energy distribution of field emitted electrons. At 0°K the new distribution width is less than $\frac{1}{3}$ of that obtained from the previous "normal energy" theory. A surprising mirror-image symmetry is observed between the zero-temperature total-energy field emission and the zero-field normal-energy thermionic emission distributions. The total-energy distribution is also derived for the zero-field thermionic case and this is found to be the mirror image of the normal-energy zero-temperature field emission distribution.

The new distribution applies to problems involving the total energy of electrons before and after emission.

EXPERIMENTAL MEASUREMENT OF THE TOTAL ENERGY DISTRIBUTION OF FIELD-EMITTED ELECTRONS. Russell D. Young and Erwin W. Müller, Field Emission Laboratory, The Pennsylvania State University, University Park, Pennsylvania (Received July 23, 1958).

Measurements of the energy distribution of field-emitted electrons with an improved retarding-potential analyzer revealed an unexpectedly narrow distribution width. Further study indicated that the tube measures the distribution in total energy of field-emitted electrons.

Experimental distributions as narrow as 0.14 ev were measured. Data were obtained at liquid hydrogen, liquid nitrogen, and room temperatures and were found to be in good agree-

ment with the new theory. The resolution of the improved analyzer is estimated to be between 0.02 and 0.03 electron volt.

The experimental results obtained from the very sensitive total energy distribution measurements serve as a further verification of the Fowler-Nordheim theory in the total energy representation.

SUM RULE FOR LATTICE VIBRATIONS IN IONIC CRYSTALS. R. Brout, Department of Physics, Cornell University, Ithaca, New York (Received March 12, 1958).

It is shown that in lattices of tetrahedral symmetry with two ions to a unit cell, in the approximation of nearest neighbor repulsive interactions, for a given wave vector $\vec{q}$,

$$\sum_{i=1}^{6} \omega_i^2(\vec{q}) = \frac{1}{\beta}\frac{18}{M} r_0,$$

where $w_i(\vec{q})$ = angular frequency of the ith mode for a given wave vector $\vec{q}$, $\bar{M} = m_+ m_-/(m_+ + m_-)$, m_+ = mass of positive ion, m_- = mass of negative ion, r_0 = interionic distance, and β is the coefficient of compressibility. This theorem serves as a useful check on numerical work as well as a relation for the downward curvature of the optical modes at small q in terms of the speed of sound. In the limit of small q, this relation becomes the first Szigeti relation. A similar theorem is true for low-density electron gases where the electrons localize on a lattice. Here one can show that

$$\sum_{i=1}^{3} \omega_i^2(\vec{q}) = \omega_{pl}^2,$$

where $\omega_{pl}^2 = 4\pi ne^2/m$, which is the classical plasma frequency. (This last relation was first derived by Kohn.)

INFRARED PROPERTIES OF HEXAGONAL SILICON CARBIDE. W. G. Spitzer, D. Kleinman, and D. Walsh, Bell Telephone Laboratories, Murray Hill, New Jersey (Received September 15, 1958).

Infrared transmission and reflectivity measurements from 1 to 25 μ (micron) have been made on several samples of green alpha (hexagonal) SiC. The residual ray bands have been observed for the extraordinary and ordinary rays. The resonance frequencies are 2.380×10^{13} sec^{-1} (12.60 μ) and 2.356×10^{13} sec^{-1} (12.73 μ) respectively. From the reflectivity the high-frequency dielectric constant is found to be 6.7. A careful analysis shows that the residual ray bands can be fitted within experimental error by the classical dispersion theory with the correct choice of the dispersion parameters. From the parameters the value 10.0 is obtained for the low-frequency dielectric constant. The effective charge is $0.94e$. Complete description of the residual ray band for the ordinary ray required, in addition to the main resonance, a weak resonance at 2.647×10^{13} sec^{-1} (11.33 μ). A study on the effects of several different surface treatments shows the reflectivities reported here are an intrinsic property of the crystal. The room temperature absorption coefficient as a function of wavelength in the range 1 to 10 μ has been determined from transmission measurements. A number of weak lattice bands are observed between 5 and 10 μ.

INFRARED PROPERTIES OF CUBIC SILICON CARBIDE FILMS. W. G. Spitzer, D. A. Kleinman, and C. J. Frosch, Bell Telephone Laboratories, Murray Hill, New Jersey (Received September 15, 1958).

Films of cubic silicon carbide have been grown by the reaction of methane with a high-purity silicon surface at 1300°C. Windows of SiC were produced by etching away portions of the silicon. Transmission and reflection measurements in the range 1 to 15 microns have been carefully analyzed according to classified dispersion theory. The dispersion parameters have been determined for the fundamental resonance at 12.60 microns. The dispersion parameters are essentially the same as those for the extraordinary ray in the hexagonal α-II form.

SPECIFIC HEATS OF SOME COPPER-RICH COPPER-NICKEL ALLOYS AT LIQUID HELIUM TEMPERATURES. G. L. Guthrie,* S. A. Friedberg, and J. E. Goldman,† Carnegie Institute of Technology, Pittsburgh, Pennsylvania (Received September 15, 1958).

Helium temperature heat capacity measurements have been made using samples containing 60, 65, 75 and 90 weight percent of copper in nickel. The results are in approximate agreement with the previous work of Keesom and

Kurrelmeyer. The more copper-rich samples have been found to obey a law of the type $c_v = \gamma T + \beta T^3$, but anomalies have been noted in the results of measurements on some of the samples containing 35 and 40 weight percent of nickel. These anomalies are attributed to a magnetic effect. Analysis of the results shows that the usual collective electron interpretation of the intrinsic magnetization of Cu-Ni alloys is oversimplified.

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LATTICE VIBRATIONS IN GERMANIUM BY SCATTERING OF COLD NEUTRONS. A. Ghose,* H. Palevsky, D. J. Hughes, I. Pelah,† and C. M. Eisenhauer,‡ Brookhaven National Laboratory, Upton, New York (Received September 9, 1958).

The dispersion relations for the optical and acoustical vibrations in the [100] and [110] directions in germanium have been determined by means of cold-neutron scattering measurements. An improved experimental method has provided data with smaller experimental error. The theoretical interpretation of the results indicates a long-range force between germanium atoms.

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ELECTRON SPIN RESONANCE OF Mn^{++} IN ALKALI CHLORIDES: ASSOCIATION WITH VACANCIES AND IMPURITIES. George D. Watkins, General Electric Research Laboratory, Schenectady, New York (Received September 12, 1958).

The spin resonance of Mn^{++} in LiCl, NaCl, and KCl is described. In NaCl, five different spectra are observed. Designated I, II, III_1, III_2, and IV, these arise from Mn^{++} ions in five different environments. These are identified as (I) Mn^{++} ions in an aggregated or precipitated state, (II) isolated Mn^{++} ions which are not near any defect, (III_1) Mn^{++} ions with a positive-ion vacancy bound in the nearest cation site, (III_2) Mn^{++} ions with a vacancy bound in the next-nearest site, and (IV) Mn^{++} ions paired off with a chemical impurity charge compensator. In LiCl and KCl only the two vacancy-Mn^{++} pairs (III_1 and III_2) are studied. In all three salts the nearest and next-nearest vacancy-Mn^{++} pairs are approximately equally stable. By studying the spectra in NaCl as the temperature is raised, the thermal dissociation of the Mn^{++}-vacancy pairs is observed, with a corresponding increase in the number of isolated Mn^{++} ions. This follows a simple mass action law giving a binding energy for the Mn^{++}-vacancy pairs of approximately 0.4 ev. An ionic point charge model of the crystalline field produced by the defects is successful in explaining several features of the spectra. However, the magnitude of the field predicted in this manner appears to be a factor of ten too low if the recent theory of Watanabe is used. This discrepancy is attributed to the role of overlap of the ion cores and/or covalency.

MOTION OF Mn^{++}-CATION VACANCY PAIRS IN NaCl: STUDY BY ELECTRON SPIN RESONANCE AND DIELECTRIC LOSS. George D. Watkins, General Electric Research Laboratory, Schenectady, New York (Received September 12, 1958).

Thermal motion of the bound positive-ion vacancy around a Mn^{++} ion in NaCl has been detected as a broadening of some of the multiplets in the Mn^{++} spin resonance spectrum. In addition, dielectric loss measurements at radio frequencies reveal a Debye loss peak which can be directly correlated with this motion. Analysis of these experiments gives the lifetime of the vacancy in the cation site nearest the Mn^{++} to be $1/\tau = 1.2\times10^{14} \exp(-E/kT)$, with $E = 0.63 \mp 0.05$ ev. Near 300°C, the lifetime of the vacancy in the next nearest site is approximately one third less. The Mn^{++}-vacancy interchange is not detected in the resonance and therefore does not set in first. The magnitude and form of the loss peak is in good agreement with the recent theory of Lidiard if the effect of both nearest and next nearest pairs is considered.

ACOUSTOELECTRIC EFFECT. R. H. Parmenter, RCA Laboratories, Princeton, New Jersey (Received December 31, 1957; revised manuscript received July 7, 1958).

A discussion is given of the three general approaches to the theory of the acoustoelectric effect – the equilibrium, the transport, and the

phenomenological approaches. The fact that these three approaches have led to mutually conflicting conclusions is due to three causes. (1) The last approach is applicable only when the mean free path of the charge carriers is much smaller than the acoustic wavelength; the first two approaches, only when the mean free path is much greater than the wavelength. (2) The transport approach of necessity ignores the contribution of charge carriers "trapped" by the acoustic wave. (3) The phenomenological approach, as developed in the previous literature, ignores the contribution to the space-charge density coming from the ion cores of a metal or the ionized impurity atoms of a semiconductor. In this paper a correct development of the phenomenological approach is given in detail for metals and for semiconductors. This is the approach appropriate under most experimental conditions, but at sufficiently low temperatures and high acoustic frequencies the equilibrium approach is appropriate in metals and semimetals. It is pointed out that the acoustoelectric effect may be considerably enhanced by the application of a magnetic field.

ELECTROLUMINESCENCE IN CUPROUS OXIDE. R. Frerichs and R. Handy, Department of Electrical Engineering, Northwestern University, Evanston, Illinois (Received August 18, 1958).

This paper reports the observation of electroluminescence in cuprous oxide. The variations in electroluminescent light output have been studied as a function of excitation frequency, wave shape, voltage, current, and power as well as for changes in ambient temperature. These basic properties are presented in graphic form and show that Cu_2O does not fit readily into either of the two general classes of electroluminescent materials, but possesses new and unusual properties of its own.

The electroluminescence can be observed in cuprous oxide plate rectifiers and in point contact structures. In the plate rectifiers changes in electrical properties known as current creep occur during excitation which are reflected in the light emission from the plates. This effect was studied in detail and a new theoretical model proposed that satisfactorily accounts for the observed changes in the electrical properties, as well as for the published observations on commercial Cu_2O rectifiers.

Unusual memory properties have been observed that permit the initial electroluminescent light output to be enhanced by prebiasing with direct currents. This phenomenon is traced to the movement of matter within the material during the biasing interval.

SULFUR VACANCY MECHANISM IN THE LUMINESCENCE OF ZnS AND CdS. A. A. Vuylsteke and Y. T. Sihvonen, Research Staff, General Motors Corporation, Detroit, Michigan (Received June 6, 1958; revised manuscript received November 3, 1958).

Experiments have been performed on the luminescence of "pure" CdS under ultraviolet excitation at room temperature. Both green and red emission were observed. The green emission at 5240A is attributed to direct recombination. The red emission at 7180A can be adequately explained on the basis of a phenomenological model proposed by Lambe and Klick. Their proposed mechanism based on the presence of silver is discarded, however, since our results indicate the action of a sulfur vacancy mechanism. A theoretical justification is presented assuming such vacancies to be responsible for the luminescence in both pure ZnS and pure CdS. The energy of the red emission in CdS is calculated to be about 1.8 ev. This is in excellent agreement with our observed value of 1.72 ev.

GALVANOMAGNETIC PROPERTIES OF GALLIUM AT LOW TEMPERATURE. J. Yahia* and J. A. Marcus, Northwestern University, Evanston, Illinois (Received August 25, 1958).

The galvanomagnetic properties of gallium single crystals in a transverse magnetic field have been investigated at helium temperatures, 77°K and 290°K. At 290°K and 77°K the galvanomagnetic properties are described according to a set of phenomenological equations, these properties then being specified by the tensors in the equations. This formalism breaks down at helium temperatures, where an apparent reduction in crystal symmetry occurs; the number of coefficients specifying the magnetoresistivity tensor according to crystal symmetry considerations is insufficient for a description of the observed galvanomagnetic properties. The results at helium temperatures can be qualitatively understood in terms of the recent fundamental theory of galvanomagnetic effects of Lifshitz,

Azbel, and Kaganov which is based on considerations involving the topology of the Fermi surface. The anomaly of a marked displacement of the maximum in the Hall rotation curve at 77°K and 290°K is accounted for in detail according to the phenomenological formalism, on the basis of the anisotropy of the Hall coefficients at those temperatures combined with a small displacement of crystallographic axes from specimen axes. Well-defined oscillations in the magnetoresistance and Hall effects, superposed on the monotonic variation of the effects, have been observed for every crystal orientation studied. The general characteristics of these oscillations are the same as those in the diamagnetic susceptibility (the de Haas-van Alphen effect).

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TOTAL CROSS SECTIONS FOR MULTIPLE ELECTRON STRIPPING IN ATOMIC COLLISIONS AT ENERGIES TO 100 kev. P. R. Jones,* F. P. Ziemba, H. A. Moses, and E. Everhart, Physics Department, University of Connecticut, Storrs, Connecticut (Received August 8, 1958).

Total cross sections have been measured for electron capture and stripping of He^+, Ne^+, and A^+ ions in single collisions of He^+ on He, Ne, and A; Ne^+ on Ne and A; and A^+ on A. Where He^+ ions are incident the cross sections are given for electron capture, σ_{10}; for electron loss, σ_{12}; and for "elastic" scattering in excess of one degree, $\sigma_{11}>1°$. Where Ne^+ and A^+ are incident the cross sections for multiple stripping $\sigma_{13}, \cdots, \sigma_{17}$ are given also. The measurements were made at 25, 50, and 100 kev and at additional energies in two cases where a maximum in the electron capture cross section was observed. Each total cross section was compiled by adding the contributions from the various angular regions into which the incident particle may be scattered. The contribution from the particles scattered between 0° and 1° was measured directly, while that for regions in excess of 1° was obtained by integrating the measured differential cross sections. In the region between 1° and 4° the differential cross section for each process was measured with high resolution and these data are presented here separately. These differential measurements supplement data previously published for angles in excess of 4°. Tables are presented showing the contribution of each of the angular regions to the various total cross sections. Large-angle scattering is found to make a significant contribution to the total cross sections for the production of the more highly ionized particles.

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SCATTERING OF CHARGED PARTICLES BY NEUTRAL ATOMS. Marvin H. Mittleman, Radiation Laboratory, University of California, Livermore, California, and Kenneth M. Watson, Radiation Laboratory and Department of Physics, University of California, Berkeley, California (Received July 24, 1958).

A new technique is described for calculation of the scattering of charged particles by atoms. This is done by means of an expansion in "incoherent fluctuations" of the state of the atom. Two limiting cases are discussed – the adiabatic and the high-energy limits. The structure and convergence of the expansion are investigated. Several variational techniques may be used within the framework of the method described. Finally, a detailed study is made of scattering by hydrogen atoms.

NUCLEAR STRUCTURE CORRECTION TO THE HYPERFINE STRUCTURE IN HYDROGEN. C. K. Iddings and P. M. Platzman, California Institute of Technology, Pasadena, California (Received September 11, 1958).

In previous papers, corrections to the hyperfine structure (hfs) in hydrogen of relative order $\alpha m/M$ have been calculated by treating the proton as a point particle with an anomalous magnetic moment in addition to its Dirac moment. In this paper the proton is treated as a particle with structure by making use of the high-energy electron-proton scattering data. Corrections of the previous work in which only a point particle was considered are calculated by using the Feynman formulation of quantum electrodynamics. It is also shown that exactly the same terms may be obtained by using the covariant Bethe-Salpeter equation.

The calculated shift of -40 parts per million (including the "recoil corrections") is not in agreement with the combined results of several experiments (-0.7 ± 6 parts per million). This

difference is attributed to meson corrections to a two-photon form factor which is taken here as the product of two (Hofstadter) single-photon form factors.

METASTABILITY OF 2s STATES OF HYDROGENIC ATOMS. J. Shapiro* and G. Breit, Yale University, New Haven, Connecticut (Received September 8, 1958).

It has been found by Breit and Teller that double photon emission is the principal cause of decay of interstellar hydrogen atoms from their metastable 2s state and the mean life corresponding to this decay was bracketed by them between upper and lower limits. In the present note an account is given of a more accurate evaluation of the transition probability $A\tau = (8.226 \pm 0.001)Z^6$ sec^{-1}, where Z is the atomic number. Relativistic effects on the atomic wave functions have been neglected in the calculations which are therefore accurate only for small Z.

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COMPTON SCATTERING OF X-RAYS FROM NONSPHERICAL CHARGE DISTRIBUTIONS. A. J. Freeman, Materials Research Laboratory, Ordnance Materials Research Office, Watertown, Massachusetts, and Solid State and Molecular Theory Group, Massachusetts Institute of Technology, Cambridge, Massachusetts (Received July 8, 1958).

The Waller-Hartree theory for the incoherent Compton scattering of x-rays is extended to include the effects of the inherent nonsphericity of atomic charge distributions. The dependence of the scattering on atomic orientation is treated by a general formalism which depends on the use of the matrix elements of a unitary representation of the group of three-dimensional rotations. Application is made to derive the one-electron scattering matrix elements from atoms with s, p, and d electrons. It is shown that by a proper averaging over all orientations of the scattering vector, "mean" scattering formulas result which may be used directly for predicting the scattering from monatomic gases.

COMPTON SCATTERING OF X-RAYS FROM ALUMINUM. A. J. Freeman, Materials Research Laboratory, Ordnance Materials Research Office, Watertown, Massachusetts, and Solid State and Molecular Theory Group, Massachusetts Institute of Technology, Cambridge, Massachusetts (Received July 26, 1958).

Hartree-Fock self-consistent field wave functions were determined for the aluminum atom and used to calculate the x-ray Compton scattering for aluminum according to the Waller-Hartree theory as extended in a previous paper. The predictions of this theory are compared with experiment and previous theoretical calculations. The theoretical results are in very good agreement with the measurements of Walker but differ from those of Laval at low values of $\sin\theta/\lambda$.

ANALYTIC WAVE FUNCTIONS. II. ATOMS WITH 1s, 2s, 2p, 3s, AND 3p ELECTRONS. R. G. Breene, Jr., Missile and Ordnance Systems Department, General Electric Company, Philadelphia, Pennsylvania (Received September 4, 1958).

The variation program for the computation of atomic wave functions which has been developed and programmed for the IBM 704 electronic data processing machine is detailed. This calculation has been set up so as to be able to handle atoms having any combination of 1s, 2s, 2p, 3s, and 3p electrons. One example of the program is provided by a calculation of the wave functions for aluminum for all degrees of ionization. Another example is provided by a calculation of the fourteen configurations for oxygen having the electron distribution $(1s)^2$ $(2s)^2$ $(2p)^3$ $(3p)$. Finally the three ^3P wave functions thus obtained are combined by means of the configuration interaction.

RELATIVISTIC K-SHELL PHOTOEFFECT. Mihai Gavrila, Department of Physics, Parhon University, Bucharest, Rumania (Received April 21, 1958; revised manuscript received October 31, 1958).

Expressions for the relativistic K-shell photoeffect cross sections, correct to first order in αZ (inclusive), are established. For this purpose a second order calculation must be carried out, that is electronic spinors correct to second order in αZ must be employed in the matrix element. The final continuum state spinor of the electron, whose exact analytic form is not known, is described by means of the Born approximation. To avoid the divergences, peculiar to the

application of this method to the pure Coulomb field, the case of the screened potential is considered at the beginning. The matrix element, which is evaluated in momentum space, remains singular in the limit of no screening. Nevertheless, it is shown that the differential cross section, as issuing from a very laborious trace evaluation, is to first order finite in this limit and has the behavior one would expect. Indeed, the zero-order approximation in αZ coincides with Sauter's formula, as it should. Further, in the nonrelativistic and extreme relativistic limits the cross section determined reduces to results established by other means.

ENERGY LEVELS IN F^{19} FROM THE $O^{18}(d,n\gamma)F^{19}$ REACTION. J. W. Butler, L. W. Fagg, and H. D. Holmgren, Nucleonics Division, United States Naval Research Laboratory, Washington, D. C. (Received August 14, 1958).

The gamma-ray threshold technique has been applied to the $O^{18}(d,n\gamma)F^{19}$ reaction in the range of deuteron bombarding energies from 1.55 to 3.36 Mev. Four gamma-ray thresholds have been observed: 1.85 ± 0.05, 2.15 ± 0.05, 2.64 ± 0.03, and 3.16 ± 0.03 Mev, corresponding to excited states in F^{19} at 7.40 ± 0.05, 7.67 ± 0.05, 8.11 ± 0.03, and 8.58 ± 0.03 Mev, respectively.

TIME REVERSAL IN NUCLEAR INTERACTIONS. Ernest M. Henley and Boris A. Jacobsohn, University of Washington, Seattle, Washington (Received July 2, 1958).

The limitations imposed by time-reversal invariance of nuclear forces have been examined for nuclear reactions, elastic double scattering (polarization) experiments, and angular correlations of gamma rays emitted from unoriented nuclei. For each of these, we have found that certain experiments, which may superficially appear to be sensitive tests of time-reversal invariance, are actually completely or partially insensitive to this symmetry. For example, in certain cases, the unitarity of the S matrix is sufficient to assure detailed balance. Such insensitivity to time-reversal invariance operates in some of the experimentally best-investigated problems. Those experiments which may be expected to be sensitive tests yield an upper limit of about 10% for that fraction of the Hamiltonian which is odd with respect to a time inversion. We have suggested experiments which may lower this limit.

GAMMA-RAY ANGULAR CORRELATION TESTS FOR TIME-REVERSAL INVARIANCE IN NUCLEAR FORCES. Boris A. Jacobsohn and Ernest M. Henley, University of Washington, Seattle, Washington (Received July 2, 1958).

A systematic method for constructing tests of time-reversal invariance in nuclear forces by means of gamma-ray angular correlations is described. The transition supplying the test consists of a mixed multipole; it must be preceded by a polarizer to produce a nuclear orientation and (in all but one case) followed by a second photon which serves as an analyzer of the final nuclear orientation. The exception is a test in which one detects the linear polarization and direction of a quantum from a nucleus with initial orientation of third degree.

A general formula for the direction of a single photon with arbitrary polarization and involving an arbitrary orientation of both the initial and final nuclear states is presented. Expressions of this type have the advantage that individual ones can be combined together in a simple way to form an arbitrary correlation formula. This is carried through numerically in one case for beta-gamma-gamma direction correlation, where the first photon is mixed $E2$ and $M1$. It is shown that such measurements must be carried out to 1 or 2% in order to better the present limit of our knowledge concerning time-reversal invariance.

REVISED WEIZSÄCKER SEMIEMPIRICAL FORMULA FOR DIFFUSE NUCLEAR SURFACES. William D. Gunter, Jr., and Robert A. Hubbs, Stanford University, Stanford, California (Received September 15, 1958).

An attempt is made to modify the Weizsäcker semiempirical mass formula to include effects of the diffuse nuclear surface indicated by recent electron scattering experiments. Volume and surface effects are combined by integrating over an assumed trapezoidal density function similar to that found experimentally. Good fits to the experimental nuclear masses are achieved with r_0 (a radius parameter) and ϵ (half the surface depth) equal to 1.081×10^{-13} cm and 1.202×10^{-13} cm, respectively. These are in reasonably good agreement with the experimental values (1.07

$\pm 0.02) \times 10^{-13}$ cm and $(1.50 \pm 0.20) \times 10^{-13}$ cm found by Hahn, Ravenhall, and Hofstadter.

ABSENCE OF ISOMERISM IN GALLIUM-65. David L. Morrison and Norbert T. Porile, Chemistry Department, Brookhaven National Laboratory, Upton, New York (Received September 12, 1958).

The formation of Ga^{65} has been investigated in the decay of Ge^{65} and in the following reactions over a wide range of bombarding energies: $Cu^{63}(\alpha, 2n)$, $Zn^{64}(\alpha, p2n)$, $Zn^{64}(d, n)$, and $Zn^{64}(p, \gamma)$. In no case was a previously reported 8-minute isomer detected.

DECAY SCHEMES OF Sm^{145} AND Pm^{145}. A. R. Brosi, B. H. Ketelle, H. C. Thomas,* and R. J. Kerr, Oak Ridge National Laboratory, Oak Ridge, Tennessee (Received August 18, 1958).

The electron capture decay schemes of Sm^{145} and Pm^{145} have been investigated. The total disintegration energy of Sm^{145} was found to be 645 ± 15 kev by measurement of the inner bremsstrahlung energy end point. The fraction of electron captures to the 61-kev level that are K-electron captures was computed to be 0.83 ± 0.02 from conversion electron-x-ray coincidence counting rates. The same coincidence method gave 0.54 ± 0.02 as the K-electron capture fraction in Pm^{145} decay to the 67-kev level in Nd^{145}. From the experimental capture ratio the transition energy was computed to be 73 ± 10 kev. The lifetime of the 61-kev level in Pm^{145} was found to be 2.6×10^{-9} sec and that of the 67-kev level in Nd^{145} was found to be 3.3×10^{-8} sec. Conversion coefficients of the gamma rays emitted in Sm^{145} and Pm^{145} decay were measured. Energy level schemes which have spin and parity assignments consistent with the experimental measurements are proposed for both isotopes.

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(n, γ) CROSS SECTIONS OF Na^{23}, I^{127}, AND Au^{197}. S. J. Bame, Jr., and R. L. Cubitt, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico (Received August 15, 1958).

The cross sections for the $Na^{23}(n, \gamma)Na^{24}$ and the $I^{127}(n, \gamma)I^{128}$ reactions have been measured by an activation method over the neutron energy range 20 kev to 1 Mev. The neutron flux was measured with a fission detector which contained a thin layer of known weight of U^{235}. The Na^{23} cross section variation with energy shows incompletely resolved resonance structure; an average curve through the data decreases as $1/v_n$ from 2.4 mb at 20 kev to 0.6 mb at 300 kev, and as $1/E_n$ from 0.6 mb at 300 kev to 0.2 mb at 1 Mev. The I^{127} cross section can be represented approximately by a straight line on a log-log plot, decreasing from 1.0 barn at 30 kev to 80 mb at 1 Mev. The $Au^{197}(n, \gamma)Au^{198}$ cross section, measured at a neutron energy of 180 kev, is 310 ± 20 mb.

DECAY OF Np^{241}. R. Vandenbosch, Argonne National Laboratory, Lemont, Illinois (Received September 8, 1958).

The decay of a 16-minute neptunium activity attributed to Np^{241} has been studied with anthracene and sodium iodide scintillation counters. The principal mode of decay appears to be a beta group decaying to the ground state of Pu^{241} with a beta end-point energy of 1.36 ± 0.10 Mev.

FREE ANTINEUTRINO ABSORPTION CROSS SECTION. I. MEASUREMENT OF THE FREE ANTINEUTRINO ABSORPTION CROSS SECTION BY PROTONS. Frederick Reines and Clyde L. Cowan, Jr.,* Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico (Received September 8, 1958).

The cross section for the reaction $p(\bar{\nu}, \beta^+)n$ was measured using antineutrinos $(\bar{\nu})$ from a powerful fission reactor at the Savannah River Plant of the United States Atomic Energy Commission. Target protons were provided by a 1.4×10^3-liter liquid scintillation detector in which the scintillator solution (triethylbenzene, terphenyl, and POPOP) was loaded with a cadmium compound (cadmium octoate) to allow the detection of the reaction by means of the delayed coincidence technique. The first pulse of the pair was caused by the slowing down and annihilation of the positron (β^+), the second by the capture of the neutron (n) in cadmium following its moderation by the scintillator protons. A second giant scintillation detector without cadmium loading was used above the first to provide an anticoincidence signal against events induced by cosmic rays. The antineutrino signal was related to the reactor by means of runs

taken while the reactor was on and off. Reactor radiations other than antineutrinos were ruled out as the cause of the signal by a differential shielding experiment. The signal rate was 36 ±4 events/hr and the signal-to-noise ratio was 1/5, where half the noise was correlated and cosmic-ray associated and about half was due to non-reactor-associated accidental coincidences. The cross section per fission $\bar{\nu}$ (assuming 6.1 $\bar{\nu}$ per fission) for the inverse beta decay of the proton was measured to be $(11 \pm 4) \times 10^{-44}$ cm$^2/\bar{\nu}$ or $(6.7 \pm 1.5) \times 10^{-43}$ cm^2/fission. These values are consistent with prediction based on the two-component theory of the neutrino.

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FREE ANTINEUTRINO ABSORPTION CROSS SECTION. II. EXPECTED CROSS SECTION FROM MEASUREMENTS OF FISSION FRAGMENT ELECTRON SPECTRUM. R. E. Carter, F. Reines, J. J. Wagner, and M. E. Wyman,* Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico (Received September 8, 1958).

A measurement of the electron spectrum from the thermal-neutron fission of U^{235} is described. From this spectrum the antineutrino spectrum is calculated, and on the basis of the two-component theory of the antineutrino a predicted average cross section for the absorption of antineutrinos by protons is $(6.1 \pm 1) \times 10^{-43}$ cm^2/fission. This agrees with the measured cross section of $(6.7 \pm 1.5) \times 10^{-43}$ cm^2/fission. The four-component theory of the antineutrino would have predicted $(3.05 \pm 0.5) \times 10^{-43}$ cm^2/fission.

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SCINTILLATION STUDIES OF SOME NEUTRON-DEFICIENT ISOTOPES OF LUTECIUM. L. T. Dillman, R. W. Henry, N. B. Gove, and R. A. Becker, Physics Department, University of Illinois, Urbana, Illinois (Received July 23, 1958).

Lu^{170}, Lu^{172}, Lu^{173}, and Lu^{174} activities were produced by bombarding Lu_2O_3 with bremsstrahlung from the University of Illinois betatrons. Gamma rays of energy 0.083, 0.190, 0.245, and 2.04 Mev were associated with the decay of Lu^{170}. A gamma-gamma coincidence experiment showed that the 2.04-Mev gamma ray was coincident with the three low-energy transitions. Gamma rays of energy 0.079, 0.113, 0.181, 0.203, 0.325, 0.370, 0.525, 0.820, 0.900, and 1.09 Mev were associated with the electron-capture decay of 6.7-day Lu^{172}, the isotope studied in the most detail. Levels of energy 0.0787, 0.2602, 0.3731, 0.5769, 0.9015, 1.082, and 1.99 Mev above the ground state have been assigned to Yb^{172} by gamma-gamma coincidence measurements and energy considerations. Gamma rays of energy 0.022, 0.079, 0.113, 0.145, 0.176, 0.274, 0.335, 0.440, 0.550, and 0.640 Mev were assigned to transitions between levels of Yb^{173}, while gamma rays of energy 0.077, 0.084, 0.113, 0.176, 0.230, 0.275, 0.990, and 1.245 Mev were associated with the decay of Lu^{174}. A summary of all gamma-gamma coincidence experiments involving Lu^{173} and Lu^{174} is included in this paper. The 0.084-Mev transition associated with the decay of Lu^{174} was interpreted to be the first excited level of Hf^{174}. A rough calculation of the K-conversion coefficient of this transition yielded $\alpha_K \leq 2.5$.

NEUTRON THRESHOLDS IN THE $V^{51}(p,n)Cr^{51}$, $Mn^{55}(p,n)Fe^{55}$, $Zn^{70}(p,n)Ga^{70}$, AND $As^{75}(p,n)Se^{75}$ REACTIONS. C. R. Gossett and J. W. Butler, Nucleonics Division, United States Naval Research Laboratory, Washington, D. C. (Received August 7, 1958).

The two-counter slow-to-fast ratio technique has been used with proton energies up to about 2 Mev in a study of neutron thresholds from the following four reactions. In the $V^{51}(p,n)Cr^{51}$ reaction, the ground-state threshold was measured to be 1.564 ± 0.002 Mev. No excited states were observed in the region of excitation from zero to 0.41 Mev. In the $Mn^{55}(p,n)Fe^{55}$ reaction, the ground-state threshold was measured to be 1.034 ± 0.002 Mev. Excited-state thresholds were found at 1.455 ± 0.003 and 1.982 ± 0.002 Mev, corresponding to energy levels in Fe^{55} at 0.414 ± 0.003 and 0.931 ± 0.002 Mev, respectively. In the $Zn^{70}(p,n)Ga^{70}$ reaction, the ground-state threshold was measured to be 1.457 ± 0.002 Mev. No excited states were observed in the region of excitation from zero to 0.53 Mev. In the $As^{75}(p,n)Se^{75}$ reaction, the ground-state threshold was measured to be 1.669 ± 0.002 Mev. An excited-state threshold was found at 1.960 ± 0.002 Mev, corresponding to an energy level in Se^{75} at 0.287 ± 0.002 Mev. A two-counter detector of high sensitivity and a low-background experimental arrangement are described.

CLASSIFICATION OF THE ENERGY LEVELS OF ODD-MASS NUCLEI IN THE HEAVY-ELEMENT REGION. F. S. Stephens, Frank Asaro, and I. Perlman, Radiation Laboratory, University of California, Berkeley, California (Received August 7, 1958).

Most of the data available on energy levels in odd-mass nuclei of the heaviest elements have been summarized and evaluated. The observed levels have been classified according to the level diagrams calculated by Nilsson for nuclei with prolate spheroidal deformations. Qualitatively, the agreement between the data and the Nilsson diagrams is very good.

DISINTEGRATION SCHEME OF Zn^{65}. G. I. Gleason, Abbott Laboratories, Oak Ridge, Tennessee (Received April 14, 1958).

Spectroscopic-coincidence techniques have been employed to re-examine the electron capture rate, branching ratio, and positron rate of Zn^{65}. Decay by positron emission occurs to the extent of $(1.70 \pm 0.10)\%$. Electron capture to the excited state was found to be associated with $(51.3 \pm 3.0)\%$ of the disintegrations, significantly higher than the 44-46% reported in previous investigations.

RADIATION DAMPING IN NUCLEAR MAGNETIC RESONANCE. A. Szöke and S. Meiboom, Department of Applied Mathematics, The Weizmann Institute of Science, Rehovot, Israel (Received August 1, 1958).

The effect of radiation damping on nuclear magnetic resonance spectra has been demonstrated experimentally. Observations on a nuclear two-level maser, obtained by flipping the magnetization through about 180°, are reported.

PROTON-PROTON SCATTERING AT 19.8 Mev. Jack W. Burkig,* J. Reginald Richardson, and Glen E. Schrank,† Department of Physics, University of California, Los Angeles, California (Received August 13, 1958).

An experimental measurement of the angular distribution of the scattering of 19.8-Mev protons by protons is described. The scattering material was hydrogen gas and detection was by scintillation counters. The cross section as a function of center-of-mass scattering angle reveals a minimum at 26° where $d\sigma/d\omega = 22.6 \pm 0.3$ mb/steradian. The measurements range from 14° where $d\sigma/d\omega = 59.7 \pm 2.0$ to 90° where $d\sigma/d\omega = 24.6 \pm 0.3$ mb/steradian and include measurements at 15 angles. The phase-shift analysis of the data is as yet incomplete.

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SMALL-ANGLE PROTON-PROTON SCATTERING AT 20 Mev. Herbert N. Royden* and Byron T. Wright, Department of Physics, University of California, Los Angeles, California (Received August 13, 1958).

The differential cross section for the scattering of 19.8-Mev protons by protons has been measured for angles between 18° and 35° in the center-of-mass system, detection being by photographic emulsion placed in a scattering camera. Cross sections were measured simultaneously at all angles and azimuths. A run with analyzing slits closed served to evaluate the small slit-edge correction. The accuracy of the cross-section measurements is approximately 2.5% at all angles except 18°, where the accuracy is about 3%.

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HIGH-ENERGY MAXIMA IN THE (π, p) CROSS SECTIONS. Robert K. Adair, Brookhaven National Laboratory, Upton, New York (Received September 5, 1958).

It is pointed out that the consideration of causality requires that any description of the maximum in the (π^-, p) total cross section at 800-Mev π^- energy and of the maximum in the (π^+, p) cross section at 1200 Mev is necessarily equivalent to a description in terms of resonances and hence in terms of nucleon isobars.

HYPERON-ANTIHYPERON PRODUCTION IN NUCLEON-ANTINUCLEON COLLISIONS AND THE RELATIVE Σ-Λ PARITY. Saul Barshay,* Brookhaven National Laboratory, Upton, New York (Received September 8, 1958).

A discussion is given of hyperon-antihyperon production in nucleon-antinucleon collisions near threshold. The rate for the reaction and

the polarization of the outgoing baryons are calculated in terms of three amplitudes characterizing the transition operators in the two cases of even and odd relative Σ-Λ parity. In terms of these amplitudes, a correlation function which gives the angular correlations between the pion momenta from the subsequent decay of the hyperon and antihyperon, and the vectors involved in the production process, is given for each relative parity. The possibility of this class of experiments being useful in determining the relative Σ^0-Λ parity, as well as the relative charged Σ-Λ parity, is discussed.

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"ANOMALOUS" SCATTERING OF μ MESONS. Shuji Fukui, Department of Physics, Osaka University, Osaka, Japan, and Takashi Kitamura and Yuzuru Watase, Institute of Polytechnics, Osaka City University, Osaka, Japan (Received August 21, 1958).

A mu-meson scattering experiment in which the mesons are required to traverse a thick block of iron and stop and decay in a thin layer carbon, is reported. Any uncertainty in the identity of the scattered particle has thus been eliminated, and further, the momentum of the particles is well defined. The observed angular distribution of the scattered mu mesons in the momentum range $(1_{-0.2}^{+0.15})$ Bev/c has been found to be in good agreement with the distribution predicted from the Coulomb scattering theory for extended nuclei obtained by Cooper and Rainwater. There is thus no indication from the present experiment for any anomalous scattering of mu mesons near 1-Bev/c momentum.

The angular distribution of scattering of those particles which traversed the iron absorber but did not necessarily stop and decay in the carbon layer was not in good agreement with the Cooper and Rainwater theory, there being more than the expected number of particles scattered through large angles. It is shown, however, that the predicted scattering distribution, at large angles (assuming no anomalous contribution), arises almost entirely from the scattering of particles in the 1-2 Bev/c region, and therefore is very sensitive to the assumed intensity in this region. It is concluded that the results from this part of the experiment cannot be accepted as evidence favoring the existence of anomalous scattering.

The experimental results of other authors on the scattering of energetic mu mesons are summarized and discussed. It is concluded that the evidence for anomalous interactions is not strong.

COSMIC-RAY LATITUDE SURVEY ALONG 145° EAST LONGITUDE USING AN AIRBORNE NEUTRON MONITOR. J. R. Storey, Physics Department, University of Tasmania, Hobart, Tasmania (Received May 5, 1958; revised manuscript received October 13, 1958).

An account is given of a survey of the cosmic-ray nucleonic component along the 145° East longitude between geographic latitudes 34°N (Tokyo) and 52°S. The instrument used was a Simpson type neutron monitor installed in a Lincoln bomber and measurements were made at a pressure altitude of 20 000 ft (475 g cm^{-2}). A check on the equipment performance was provided by covering the entire route twice. A Forbush intensity decrease was encountered during the southbound section between latitudes 5°S and 36°S. Its latitude dependence in this range is the subject of the next paper. The cosmic-ray equator was located at 7.1°N geographic (2.4°S geomagnetic), and the south cosmic-ray knee, defined as the latitude south of which there is no further increase of intensity with latitude, occurred at 43.5°S geographic (52.3°S geomagnetic). The survey north of Melbourne (38°S geographic) was completed between July 18 and August 6, 1957. Flights south from Melbourne were made on August 19 and 21, 1957.

LATITUDE DEPENDENCE OF A FORBUSH-TYPE COSMIC-RAY INTENSITY DECREASE OBSERVED AT AIRCRAFT ALTITUDE. J. R. Storey, Physics Department, University of Tasmania, Hobart, Tasmania (Received May 5, 1958; revised manuscript received October 13, 1958).

During the aerial survey of the cosmic-ray nucleonic component along the longitude 145°E described in the previous paper, two southbound flights between geographic latitudes 5°S and 36°S were made under depressed cosmic-ray intensity following the Forbush-type decrease commencing August 4, 1957. Comparison of the intensity vs latitude plot with that obtained during the northbound flights over the same route when quiet cosmic-ray conditions prevailed, enabled the

latitude dependence of the decrease to be determined. It is found that for the event investigated, the percentage decrease was independent of latitude over the range 5°S to 36°S geographic (14°S to 45°S geomagnetic) at the altitude of observation ($475\,g\,cm^{-2}$). However, comparison of data from two fixed stations, Lae (16°S geomagnetic) and Hobart (52°S geomagnetic), showed that this latitude independence did not extend to sea level.

PRELIMINARY RESULTS OF THE MOMENTUM DEPENDENCE OF THE ASYMMETRY IN MUON DECAY. Hans Kruger and Kenneth M. Crowe, Radiation Laboratory, University of California, Berkeley, California (Received September 9, 1959).

Positive muons from the Berkeley 184-inch synchrocyclotron were stopped in various materials and the asymmetry of positrons from their decay was determined by using a magnetic spectrometer method. The measurements of the polarization are in agreement with that predicted by the two-component neutrino theory.

The product of the muon beam polarization and of ξ, the parameter of the two-component neutrino theory, was measured as 0.89 ± 0.09.

Ξ^- CAPTURE REACTIONS IN HYDROGEN. S. B. Treiman,* Brookhaven National Laboratory, Upton, New York (Received September 8, 1958).

In the capture reaction $\Xi^- + p \rightarrow \Lambda + \Lambda$, the asymmetries in the Λ decays constitute an excellent analyzer for determining the polarization pattern of the Λ's and hence the nature of the final orbital states involved. Such information, together with evidence concerning alternate capture channels $\Xi^- + p \rightarrow \Xi^0 + n$, $\Xi^- + p \rightarrow \Lambda + \Lambda + \gamma$, may permit a determination of the parity of Ξ relative to that of the nucleon.

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PHOTOPRODUCTION OF PION PAIRS IN HYDROGEN. Michel Bloch and Matthew Sands, The California Institute of Technology, Pasadena, California (Received September 2, 1958).

The photoproduction of pion pairs has been observed by detecting, in a magnetic spectrometer, the negative pions which emerged at 60° and at 120° from a hydrogen target in the bremsstrahlung beam of an electron synchrotron. The yields of negative pions "per equivalent quantum" were measured for several values of the pion energy and the bremsstrahlung cutoff energy. From the variations of the yields with bremsstrahlung cutoff energy, the cross section for the emission of negative pions was obtained. The cross section shows no large dependence on the pion angle from 90° to 150° in the c.m. system. The integral of the cross section over the negative pion energy is consistent with a constant value of about $4 \times 10^{-30}\,cm^2$/sterad for photon energies between 600 and 1100 Mev. The observed dependence of the cross section on pion energy has been compared to some phenomenological models.

PION SPECTRUM IN RADIATIVE K_{π}^{+} DECAY. J. D. Good, The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois (Received September 2, 1958).

The π^+ energy spectrum is calculated for the process $K^+ \rightarrow \pi^+ + \pi^0 + \gamma$, taking into account the processes of internal bremsstrahlung and of direct dipole emission, both $E1$ and $M1$ transitions being permitted with parity nonconservation for weak decays. For the π^+ energy range 55-75 Mev, which has been examined in some recent investigations, the internal bremsstrahlung process alone leads to an expectation of 1.0 anomalous K_{π}^{+} decay in the 8653 K^+ decays examined, quite compatible with the observation of two anomalous K_{π}^{+} decays in these data. For reasonable values of the dimensionless parameters $A(\mu/M)^4$ and $B(\mu/M)^4$ which specify the dipole transition strengths (that is, with $A=B=1$ and M equal to the K-particle mass), it appears that their main contribution will arise from the interference of the $E1$ direct transition with the internal bremsstrahlung term, increasing or decreasing the above estimate by about 20%.

VARIATIONS IN THE COSMIC-RAY RIGIDITY SPECTRUM. K. G. McCracken, Physics Department, University of Tasmania, Hobart, Tasmania (Received July 16, 1958).

Variations in the counting rates of two different high-latitude neutron monitors, a high-latitude meson telescope, and a low-latitude neutron monitor are studied for the period August 1956 to January 1958. A long-term decrease in counting rate was observed at all stations, superposed on which there were numerous short-term

variations of from 3 to 30 days duration. The long-term variation in neutron counting rate at high latitudes was four times greater than that at low latitudes, indicating that the change in the cosmic-ray spectrum was most pronounced at low rigidities. The high-latitude short-term variations in neutron counting rate were about 2.5 times greater than those at low latitudes, the ratio varying from event to event. This is interpreted as evidence that the spectrum changes during short-term variations are less strongly dependent upon rigidity than in the case of the long-term variation, and that they are of a variable character. Comparison of the neutron data with simultaneous meson data supports this view. It is concluded that the long- and short-term variations in intensity are produced by different mechanisms.

ELASTIC PROTON-PROTON COLLISIONS AT 6.2 Bev IN NUCLEAR EMULSIONS. R. M. Kalbach,* J. J. Lord, and C. H. Tsao, University of Washington, Seattle, Washington (Received September 8, 1958).

Ilford *G-5* emulsions were exposed to the 6.2-Bev proton beam of the Berkeley Bevatron. Of the interactions located, 31 could be classified as elastic collisions of beam protons with free hydrogen nuclei. After correction for scanning efficiency and background events, an elastic scattering cross section of 8.8 ± 2.0 mb was obtained. The center-of-mass system angular distribution of elastically scattered protons is sharply peaked in the forward and backward directions and is in fair agreement with the prediction of a uniform optical model with a radius of 0.94×10^{-13} cm, a phase shift of 0.00 radian, and an opacity of 0.81. The results are compared with those of previous experiments.

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INELASTIC PROTON-PROTON COLLISIONS AT 6.2 Bev. R. M. Kalbach,* J. J. Lord, and C. H. Tsao, Department of Physics, University of Washington, Seattle, Washington (Received September 8, 1958).

Inelastic, 6.2-Bev proton-proton collisions in nuclear emulsions are examined using the internal beam of the Berkeley Bevatron. Multiple scattering, grain density, range, and angle measurements yield the momentum spectra and angular distributions of secondary pions and protons together with the cross sections for accessible final states. The results indicate a cross section of 7.3 ± 4.6 mb for two-prong events, 12.1 ± 2.4 mb for four-prong events, 2.7 ± 0.6 mb for six-prong events, 0.3 ± 0.3 mb for eight-prong events, and 0.2 ± 0.2 mb for ten-prong events, giving a total inelastic cross section of 22.6 ± 5.3 mb. The average charged-pion multiplicity was found to be 1.9 ± 0.3 and the value of K, the average degree of inelasticity, 0.49 ± 0.05. Comparison of observed partial inelastic cross sections with the predictions of the Fermi statistical theory indicates that this theory underestimates the relative probability for states with high meson multiplicity. Considerable forward and backward peaking was observed in the center-of-mass system angular distributions for secondary protons and, to a lesser extent, for secondary charged pions. Center-of-mass system momentum distributions for secondary charged pions peak at lower momenta than predicted by the statistical theory, while those for protons peak somewhat higher than predicted. Effects are discussed which could account for these discrepancies.

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APPLICATION OF LINEAR NETWORK ANALYSIS TO FEYNMAN DIAGRAMS. Jon Mathews, California Institute of Technology, Pasadena, California (Received September 2, 1958).

An analogy between a linear passive electrical network and a Feynman diagram is pointed out. The power dissipated in the network is closely related to the denominator of the Feynman matrix element, and this similarity provides a very simple proof of Nambu's results concerning the location of the singularities of Green's functions.

PROOF OF DISPERSION RELATIONS FOR THE PRODUCTION OF PIONS BY REAL AND VIRTUAL PHOTONS AND FOR RELATED PROCESSES. Reinhard Oehme, Enrico Fermi Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois, and John G. Taylor,* Department of Physics, University of Maryland, College Park, Maryland (Received August 27, 1958).

It is shown that the amplitudes for the production of pions by photons and electrons (vir-

tual photons), as well as for elastic photon-proton and photon-deuteron scattering, have certain analytic properties as functions of energy and momentum transfer. These properties are proven on the basis of the axioms of field theory, especially local commutativity and the spectral conditions. They guarantee the validity of the usual dispersion relations for restricted values of the invariant momentum transfer. In the construction of these dispersion formulas, the electromagnetic interaction is treated in lowest order. The residua of the poles arising from the single-particle intermediate states are related to the corresponding vertex functions. For fixed values of the total energy the absorptive parts of the amplitudes are analytic functions of momentum transfer; they are regular inside certain ellipses. These properties make it possible to continue the absorptive parts into the "unphysical regions" appearing in the nonforward dispersion relations by means of partial-wave expansions.

In the Appendix a brief survey is given of the limitations in momentum transfer or the unphysical mass restrictions, which one encounters in the proof of dispersion relations for some elastic scattering processes.

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CONSTRUCTION OF THE DIRAC EQUATION CENTRAL POTENTIAL FROM PHASE SHIFTS AND BOUND STATES. Francisco Prats and John S. Toll, Department of Physics, University of Maryland, College Park, Maryland (Received August 29, 1958).

The connection between phase shifts, bound-state energies, and the potential is studied for a Dirac particle in a spherically symmetric potential. An explicit method is developed for the construction of the potential from the scattering and bound-state data for a single angular momentum and parity. The technique used in this relativistic problem is an extension, appropriately generalized to matrices, of the methods used by Jost and Kohn for the nonrelativistic case. For potentials with $\int_0^\infty r^n |V(r)|\, dr$ finite for $n=0, 1,$ and 2, it is shown that a spectral function can be constructed from the phase shifts, the bound-state energies, and the norm of the bound-state wave functions. A generalization of the Gel'fand and Levitan method is developed for the determination of the potential from the spectral function. First, eigenvectors associated with two different potentials are related; from the operator that connects the two systems of eigenfunctions, a modified kernel is defined which satisfies an integral equation determined by the spectral function and eigenfunctions corresponding to a "comparison potential" and the spectral function associated with the "unknown potential." Second, the potential difference is obtained by the differentiation of a certain combination of the elements of the modified kernel.

These properties lead to the following method for the construction of the potential: (1) the spectral function is determined from the data for both positive and negative energies; (2) with the spectral function for the unknown potential and the spectral function and eigenfunctions of a convenient comparison potential, the integral equation for the modified kernel is constructed; (3) from the solution of the integral equation the difference between the unknown and the comparison potentials is determined.

INVARIANTS OF GENERAL RELATIVITY AND THE CLASSIFICATION OF SPACES. Louis Witten, RIAS, Baltimore, Maryland (Received June 11, 1958).

A unique equivalence is established between the Riemann curvature tensor and two spinors. The fourteen invariants which can be constructed from the curvature tensor are listed in terms of the spinors. The vanishing of the invariants for several different types of spaces is described. A classification of Einstein spaces is made together with a few additional remarks concerning classification of spaces.